

# MICROPETROLOGY

## FOR BEGINNERS

J. E. W. RHODES

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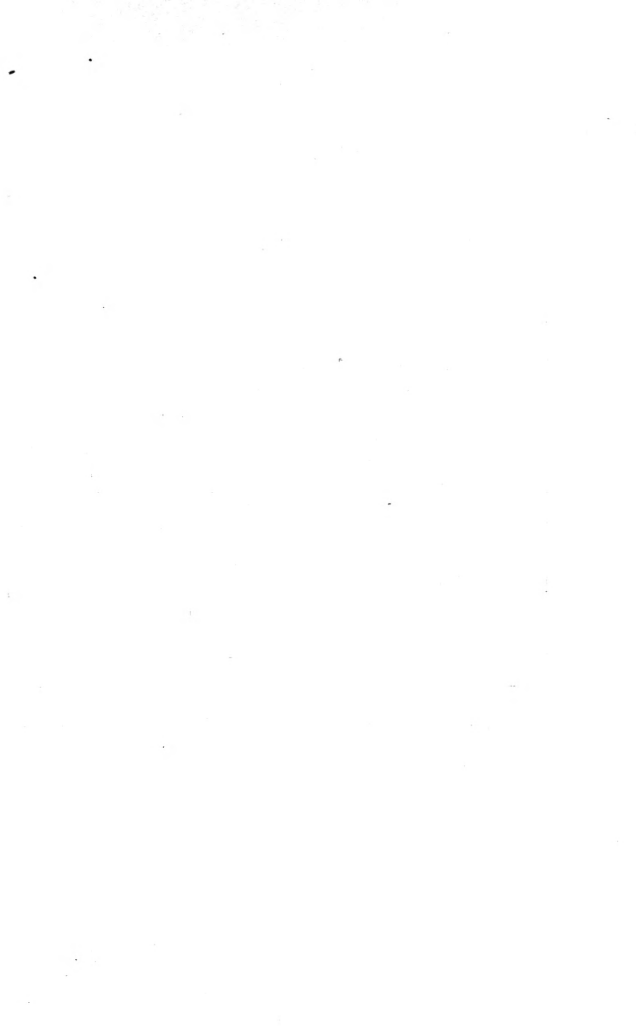
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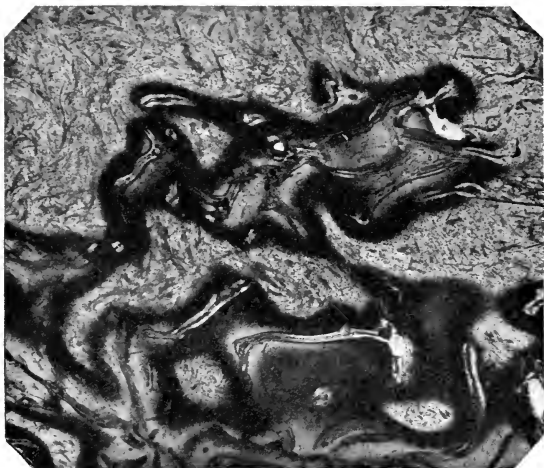




MICROPETROLOGY FOR  
BEGINNERS







Glassy Pantellerite  $\times 30$ , Isle of Pantellaria, showing flow structure.

*(Photomicrograph by C. H. Sidebotham.)*

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# MICROPETROLOGY FOR BEGINNERS

AN INTRODUCTION TO THE USE OF THE  
MICROSCOPE IN THE EXAMINATION  
OF THIN SECTIONS OF  
IGNEOUS ROCKS

BY

AMES.  
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WITH A PREFACE BY

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WITH NUMEROUS ORIGINAL ILLUSTRATIONS

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## AUTHOR'S NOTE

THE great increase in the popularity of Petrology in recent years has made the want of a practical elementary text-book more keenly felt, especially by teachers in evening technical schools. The subject is required for Inter. B.Sc. in Geology (London); but unfortunately it is impossible to gain the necessary practical information on the handling of the petrological microscope either from the general text-books on Geology or the specialised books on Petrology. The latter, as far as England is concerned, are few in number, expensive, and they do not give the elementary practical information that a student needs; although, on the other hand, they go very much further into the subject than is advisable for a beginner. This little book has been written to bridge over this gap and to give the student and the amateur microscopist that practical knowledge of Micropetrology which hitherto he

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could only learn from the verbal instructions of a teacher. An account is first given of the method of using the microscope, then the optical properties of rock-forming minerals are treated in a general way. A detailed account of the study of a carefully chosen series of igneous rocks follows, the method of identifying each mineral being given as each new rock introduces them. It is suggested that the student should procure slides<sup>1</sup> of most if not all of the rocks described, and work through them systematically in the order given, making sketches, preferably in colour, as he goes along. Chapter VII. gives a synopsis of the igneous rocks, showing the relationships of the different types to each other in a concise form. In the Appendices is given some more advanced methods of identifying rock-forming minerals in thin section, and a table for the identification of rock-forming minerals in thin section. A glossary-index is added, which should be a great help to all beginners in Petrology.

<sup>1</sup> A set of slides to illustrate this book can be obtained from Messrs. Flatters & Garnett, Dover Street, Manchester, and Messrs. W. Watson & Sons, Ltd., 313 High Holborn, London, W.C.

I owe many improvements and suggestions to my friends Mr. E. L. Rhead, F.I.C., and Mr. C. H. Sidebotham, A.R.S.M., F.G.S., of the Municipal School of Technology, Manchester, whose kindness in taking so much personal interest in the book has been a great encouragement to me. To Mr. Sidebotham I am also indebted for the Preface, which he has so kindly contributed, for help in revising proofs, and for the Frontispiece.

I have great pleasure in acknowledging the kind assistance of Dr. W. G. Rhodes, Head of the Physic Department, Royal Technical Institute, Salford, who has read through the proofs of the optical portion of the book. For the loan of blocks of their respective microscopes, I owe thanks to Messrs. J. Swift & Son, and W. Watson & Sons.



## PREFACE

IN recommending the following pages to the attention of students and teachers of Practical Petrology, I may say that some fifteen years' teaching experience in this subject had fully convinced me of the want of such a work. It is not intended in any way to take the place of well-known works, such as "Hatch's" and "Harker's" text-books, but to supplement them, and to serve as a handy work of reference for the laboratory; and I venture to think that it supplies certain information in which the latter works are lacking, but which is very essential to the beginner in this subject, and is not altogether easy of access.

Some attempt was made to supply it, with partial success, in the Manchester School of Technology, by a series of printed papers; but this plan had certain obvious disadvantages, which it is hoped this book will overcome.

In addition to the study of a typical series of sections as recommended, and which should be easily accessible to all petrological students, the work contains some information as to the preparation of material, the choice of the microscope, and the optical properties of minerals—all of which should be of value to the beginner.

Lastly, the cost of the work will not, I think, act as a deterrent to any student who is really anxious to acquire the rudiments of the subject; and having done so much, its inherent fascination can be relied on to induce him to pursue his studies further.

C. HOWARD SIDEBOTHAM.

MUNICIPAL SCHOOL OF TECHNOLOGY,  
MANCHESTER, *Sept.* 1911.

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# MICROPETROLOGY FOR BEGINNERS

## CHAPTER I

### THE EXAMINATION OF THIN SECTIONS OF ROCKS UNDER THE MICROSCOPE

**The Preparation of Thin Sections.**—The preparation of thin sections of rocks is neither expensive nor difficult. Most dealers will prepare them for about one shilling each; or the microscopist who can afford the time may prepare his own for a trifling outlay.

The materials required are :—

$\frac{1}{2}$ lb. of coarse emery . . . . .	2d.
$\frac{1}{2}$ lb. of fine flour emery . . . . .	2d.
1 dozen glass slips (3 inches by 1 inch) for slides	3d.
$\frac{1}{4}$ oz. of round $\frac{3}{4}$ -inch No. 2 cover-glasses . . .	11d.
1 oz. of Canada balsam in xylol . . . . .	7d.
A glass plate not less than 4 inches square (an old photographic negative will do).	

A thick flat iron plate for grinding on (where obtainable a flagstone with a flat surface will be found excellent).

The above is the minimum outfit. Most authors advise the use of a Water of Ayr stone for

the final polishing, but the outfit just named has been found quite sufficient for most rocks. The beginner is advised to select a fine-grained rock free from quartz, such as a dolerite, for his first essay. He should not attempt to prepare his own slides until he has studied good preparations, so as to familiarise himself with the finished appearance of the slides. The *modus operandi* is as follows:—A small chip of the rock, say about 1 inch square by  $\frac{1}{8}$  inch thick, is detached from the rock specimen by means of a hammer. A little coarse emery and water is then placed on the iron plate or stone and the chip rubbed to and fro or with a circular motion on the plate, holding it down with the first finger and thumb. The emery and water are renewed as often as necessary, and grinding continued until a perfectly flat surface of sufficient area has been produced. The chip is then washed, transferred to the glass plate, and ground with flour emery and water until smooth and perfectly free from scratches. It is then dried. A drop of Canada balsam is placed on the centre of a glass slip previously cleaned, and heated gently, taking care that bubbles do not appear in the balsam through too rapid heating. At intervals a small portion of the balsam is taken up on the point of a knife and pressed against

the thumb nail. If it hardens at once but does not become brittle, the balsam is ready; otherwise the heating must be continued. When the balsam is ready, the chip, previously warmed, is placed smooth side down in the balsam, and kept firmly pressed down until the balsam is cold and hard. The rough surface of the chip is now ground with coarse emery and water on the iron plate until it becomes semi-transparent and of the thickness of a sixpence. It is then transferred to the glass plate and ground with fine emery and water until on examining it through the microscope it is deemed sufficiently thin. This point is best ascertained by noting the "polarisation colours" of the chief mineral constituents, which are given in the sequel. It may now be transferred to a clean glass slip, if desired, by warming so as to melt the balsam and sliding it on to its new glass slip, which has already been prepared with balsam. There is some risk of breaking the section in so doing, and the process may be omitted without disadvantage except to the appearance of the finished slide. A cover-glass must now be added. This is a process requiring care to avoid the development of bubbles. The best method is to place a clean cover-glass over the section and a drop of Canada balsam at

its edge. On warming the slide, the balsam is drawn under the glass by capillary attraction and fixes the cover-glass firmly on. The addition of a cover-glass not only protects the preparation, but adds much to its transparency.

**The Petrological Microscope.**—A microscope for petrological work should embody the following features (placed in order of importance):—

1. A rackwork coarse adjustment free from backlash.

2. A polariser, fitting into a ring on an arm swivelling under the stage, so that it can be thrown in and out of action.

3. An analyser, which may screw over the objective, fit over the eyepiece, or preferably slide in and out of a slot in the body tube of the microscope.

4. A 1-inch or  $\frac{2}{3}$ -inch objective and A or B eyepiece.

5. Fine adjustment by micrometer screw or lever motion.

6. A  $\frac{1}{4}$ -inch or  $\frac{1}{6}$ -inch objective and extra eyepiece (C).

7. Rotating stage having its edge graduated in degrees reading by pointer, or preferably by vernier.

Petrological microscopes usually possess also

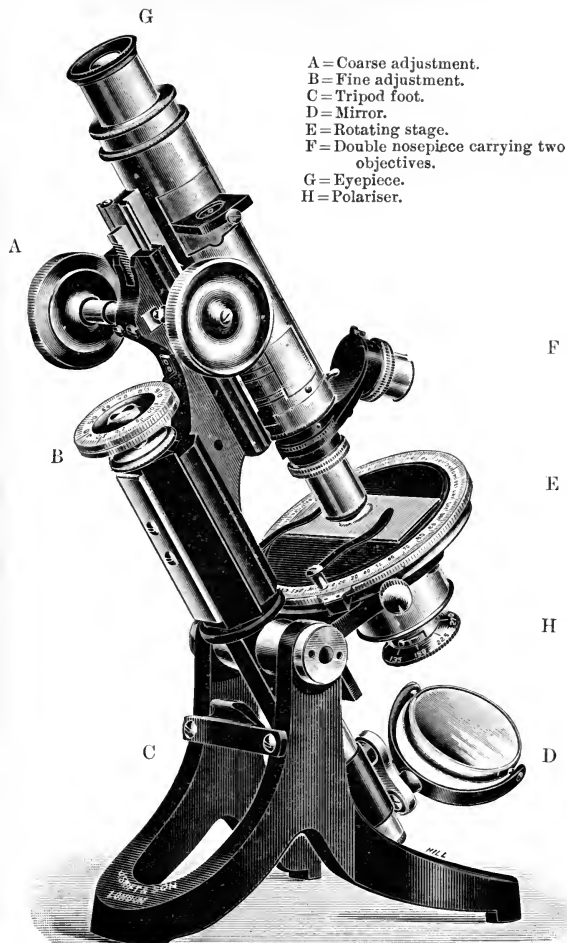


FIG. 1.—Advanced Students' Petrological Microscope, by J. Swift & Son.

a graduated milled head to the fine adjustment for measuring the thickness of objects in the slide, a condensing lens fitting over the top of the polariser, and a small lens sliding in and out of the body tube for observing interference figures ; but these are not required for elementary work. Messrs. Swift's twelve-guinea petrological stand and Messrs. Watson's praxis petrological at £9, 10s. embody these features. Most of the work, however, can be done with an ordinary microscope, without rotating stage, costing about £4 to £5, by adding a polariscope at a cost of £1.

**The Choice of a Stand.**—When choosing a stand, great care should be taken to see that it is perfectly rigid. If (as it should be) it is inclinable, the foot must be broad enough to make it perfectly steady when inclined at  $45^{\circ}$ . The choice of style of microscope, whether English or Continental, is largely a matter of individual taste. Both styles are made by English makers, but the Continental style is considerably the cheaper for various reasons. The English style—*e.g.* Swift's advanced petrological stand—has a tube length of 250 mm. and eyepieces 1.27 inches in diameter. The foot is usually a tripod. In the Continental style—*e.g.* Watson's praxis—the tube length

is either 160 mm. or 200 mm., the eyepiece gauge  $\cdot 9173$  inch, and the foot of horse-shoe shape. The Continental make is therefore

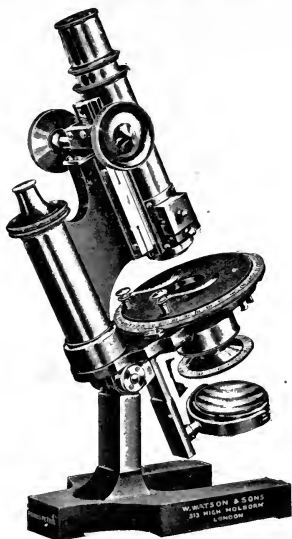


FIG. 2.—Praxis Petrological Microscope, by W. Watson & Sons, with horse-shoe foot, and Klein's Quartz Plate.

smaller and much more compact, particularly because the horseshoe foot for the same degree of steadiness is of much smaller spread than the tripod foot. If a cheap stand is to be

chosen, a horseshoe foot is more likely to give satisfaction.

**Method of using the Microscope.**—

The mirror is usually plane on one side and concave on the other, and is mounted on an adjustable arm under the stage. The plane side is used in daylight, the concave side for artificial light, the idea in each case being to transmit a beam of nearly parallel rays through the polariser. Sections are usually examined by means of light transmitted from the mirror (*transmitted light*); but it is also useful to examine them by *reflected light*. This is done by throwing the mirror out of action and sending a beam of light on to the surface of the slide by means of a bull's-eye condenser.

When focusing a 1-inch objective, the coarse adjustment alone need be used; but when a higher power ( $\frac{1}{4}$  inch or  $\frac{1}{6}$  inch) has to be focused, the objective is first lowered so as nearly to touch the slide, and then raised gently by the coarse adjustment until the object comes into view. It is then focused till quite sharp and clear by means of the fine adjustment. With practice, however, even  $\frac{1}{6}$  inch can be focused perfectly by the use of a good coarse adjustment alone.

In a petrological stand the polariser rotates

and has its edge graduated. At four positions,  $90^\circ$  apart, it is caught by a spring catch; and at these positions the diagonals of the polarising prism are parallel to the cross-threads in the eyepiece. In two of these positions,  $180^\circ$  apart, when the analyser is inserted through the slot in the body tube there is darkness in the field on looking through the eyepiece; the Nicol's prisms of the polariser and analyser are then said to be crossed. In an ordinary stand the "crossed nicols" position may be obtained by rotating either the analyser or polariser until the field is dark.

APPROXIMATE MAGNIFICATIONS ON ENGLISH AND CONTINENTAL STANDS WITH DIFFERENT OBJECTIVES.

	Magnification in Diameters.									
	Tube length 160 mm.					Tube length 250 mm.				
	3 in.	1 in.	$\frac{3}{4}$ in.	$\frac{1}{4}$ in.	$\frac{1}{8}$ in.	3 in.	1 in.	$\frac{3}{4}$ in.	$\frac{1}{4}$ in.	$\frac{1}{8}$ in.
Objective . .										
Eyepiece No. 1.	10	32	40	130	180	...	...	...	...	...
„ A.	...	...	...	...	...	16	50	65	200	300
Eyepiece No. 2.	14	45	55	180	270	...	...	...	...	...
„ B.	..	...	...	...	...	25	75	100	300	450
Eyepiece No. 3.	18	60	70	230	360	...	...	...	...	...
„ C.	...	...	...	...	...	35	100	140	400	600

## CHAPTER II

### THE OPTICAL PROPERTIES OF MINERALS

**Polarised Light.**—Light is generally considered to be a wave motion. The waves of the sea undulate in one plane, but those of light may undulate in all possible planes. If the vibrations take place in one plane only, light is said to be polarised. Since any motion can be resolved into two at right angles to each other by the parallelogram of forces, so a vibration in one plane may be considered equal to two vibrations in planes at right angles to each other. Common light contains waves vibrating in every possible plane; but each constituent can be resolved into two vibrating parallel to two fixed lines at right angles to each other. Common light is therefore equivalent to two beams of polarised light vibrating in planes at right angles to each other.

**Nicol's Prism.**—A polariser possesses the power of stopping one of these beams. It consists usually of a Nicol's prism, or *nicol* of

calcite, which is so constructed that all light polarised parallel to the shorter of its diagonals is absorbed, and the remainder of the light passing through is therefore polarised parallel to the longer diagonal. If a similar Nicol's prism or "analyser" be placed so as to intercept the rays coming from the polariser, so that its longer diagonal is at right angles to the longer diagonal of the polariser, then all the light will be stopped; for all the light, being polarised in the plane of the long diagonal of the first nicol, is absorbed by the second, because it is polarised parallel to its short diagonal. Of course, if the second nicol be held parallel to the first, the polarised light passes through without further change.

**Polarisation Colours.**—It is often said that a crystal splits up a ray of light into two rays: an ordinary and an extraordinary. The explanation is that in any crystal (other than cubic) rays of light vibrating in different planes are not transmitted with equal velocity. In a tetragonal or hexagonal crystal there are equal lateral axes differing in length from the vertical axis, or, in other words, the crystal is symmetrical about the vertical or principal axis. Now, the æther within the crystal is distributed with exactly the same symmetry—that is to say,

it will transmit light with the same velocity—in any vertical plane: *i.e.* plane at right angles to the one containing the lateral axes. If, however, the crystal is placed on its side and light transmitted through it vertically, then it is found that light polarised parallel to the principal axis (also called the optic axis) is transmitted at a different velocity from that which is polarised parallel to the lateral axis. When the light emerges from the crystal, one component will be ahead of the other. If, instead of common light, polarised light be transmitted, if the plane of polarisation be parallel or at right angles to the optic axis, it all passes through at one velocity; but otherwise the polarised light in traversing the crystal is split up into two components, polarised parallel to the vertical and lateral axis respectively. On emerging these components cannot unite to form the original beam, because one is ahead of the other—that is, it is in a different phase of vibration. On reaching the analyser, each is split up again into components polarised parallel and at right angles to the short diagonal of the nicol. The former are absorbed; the latter pass through. Now, were it not for this difference of phase, the two remaining components would be equal and opposite, and thus would neutralise each

other ; but the difference of phase prevents this except when it amounts to an exact multiple to a wave-length. Since every colour has a different wave-length, the difference in phase will be greater for some colours than for others ; and for every thickness of the crystal certain colours will have their components just equal and opposite in phase so as to neutralise each other and become extinguished. Consequently, since white light is made up of all the colours, the light passing through the crystal will appear coloured when viewed through the analyser. Different thicknesses will exclude different colours, and the residue passing through the analyser will exhibit different "polarisation" tints, or, more correctly, "interference" colours. These colours appear in a definite order as the thickness of the crystal is increased from zero upwards, and this order is called Newton's Scale. If the nicols are placed parallel instead of being crossed, the complementary colours appear, because those colours are admitted which were stopped before, whilst those that appeared before are absorbed.

## NEWTON'S SCALE

	Crossed Nicols.	Parallel Nicols.
1st Order	<ol style="list-style-type: none"> <li>1. Black</li> <li>2. Iron grey</li> <li>3. Lavender grey</li> <li>4. Grey blue</li> <li>5. Light blue</li> <li>6. Greenish white</li> <li>7. Almost pure white</li> <li>8. Yellowish white</li> <li>9. Pale straw yellow</li> <li>10. Straw yellow</li> <li>11. Light yellow</li> <li>12. Bright yellow</li> <li>13. Brownish yellow</li> <li>14. Reddish orange</li> <li>15. Red</li> <li>16. Deep red</li> </ol>	<p>Bright white White Yellowish white Brownish yellow Yellowish brown Brownish red Reddish violet Violet Light indigo Darker indigo Indigo Blue Grey blue Blue green Pale green Yellow green</p>
2nd Order	<ol style="list-style-type: none"> <li>17. Purple</li> <li>18. Violet</li> <li>19. Indigo</li> <li>20. Sky blue</li> <li>21. Greenish blue</li> <li>22. Green</li> <li>23. Lighter green</li> <li>24. Yellowish green</li> <li>25. Greenish yellow</li> <li>26. Pure yellow</li> <li>27. Orange</li> <li>28. Bright orange red</li> <li>29. Dark violet red</li> </ol>	<p>Lighter green Greenish yellow Golden yellow Orange Brownish orange Light carmine red Purplish red Violet purple Violet Indigo Dark blue Greenish blue Green</p>

NEWTON'S SCALE—(*continued*)

	Crossed Nicols.	Parallel Nicols.
3rd Order	30. Violet 31 & 32. Blue 33 & 34. Green 35. Greenish yellow 36 & 37. Rose red 38. Red	Greenish yellow Yellowish orange Red Greyish blue Greenish blue Green
4th Order	39. Violet grey 40. Greyish blue 41. Dull sea green 42. Bluish green 43. Light green 44. Light greenish grey 45. Whitish grey	Yellowish green Greenish yellow Yellowish grey Lilac Carmine Greyish red Bluish grey

It should be noticed that whilst there is a recurrence of colours from blue, through green and yellow to red, there is a gradual increase in the brightness and vividness of the tints. After the fourth order, the colours follow in such rapid succession that they cease to be separately recognisable, and the rough surface of a mineral giving them has a peculiar iridescent pinkish-grey appearance, which can best be seen in thin sections of calcite. The order of the colours in the lower orders may be seen by viewing a large sand grain between crossed nicols, when the

colours appear in concentric bands on account of the increase of thickness towards the middle.

If the tetragonal or hexagonal crystal be rotated so that its principal axis becomes parallel to the longer diagonal of the nicols, the polarised light passes through unchanged, because the crystal can only split up the light into rays polarised in directions parallel and perpendicular to the vertical axis; and here the latter component becomes zero. On reaching the analyser, the light is wholly absorbed, so that the field appears dark. If the principal axis be at right angles to the long diagonal, a precisely similar reasoning holds, and the field is also dark, or, to use the proper phrase, *extinction* has taken place.

**Extinction.**—Crystals of the *Rhombic*, *Monoclinic*, and *Triclinic Systems* differ from the above in having three unequal axes, so that there are three directions at right angles to one another in the crystal, called *axes of optical elasticity*, along which light travels with different velocities. In any section of such a crystal, only two such directions can be present, and the light is split up into two rays polarised parallel to them. Thus every section of such a crystal is light between crossed nicols, except when the axes of elasticity are parallel to the

diagonals of the polarising nicol. When this occurs, the field appears dark and *extinction* is said to take place. In the rhombic system, the axes of elasticity coincide with the crystallographic axes, so that the crystal extinguishes straight—that is, parallel to the crystallographic axes, or, what comes to the same thing, the traces of the prisms, pinakoids, or domes. In the monoclinic system, the orthodiagonal is always an axis of elasticity, and sections of crystals cut parallel to the orthopinakoid extinguish straight—*i.e.* parallel to the traces of the other pinakoids and the prisms—but all other sections extinguish when the vertical axis (shown by the prismatic cleavages or edges of the crystal) makes an angle with the diagonal of the nicol known as the *extinction angle*. Triclinic crystals always extinguish obliquely, because there are three unequal axes meeting at angles which are never right angles. No one axis has any advantage over the others; so that if one axis were to be parallel to an axis of optical elasticity, the optical symmetry would be more perfect than the crystallographic symmetry, and such an event is alike contrary to theory and practice.

It can easily be shown that in these rhombic, monoclinic, and triclinic crystals there are in every section two directions, lying in the plane

containing the axes of greatest and least elasticity in which the two rays, ordinary and extraordinary, travel with the same velocity, so that there is no difference of phase between them, and when they reach the analysing nicol they will be absorbed and the field will remain dark. Strictly speaking, however, on account of chromatic dispersion and internal conical refraction—phenomena which are beyond the scope of this book—such sections do admit a little light through the analyser, but usually of a dull grey tint. These directions are thus analogous to the optic or principal axis of tetragonal crystals. They are called optic axes; and since there are two of them, all such crystals are said to be biaxial, whereas the tetragonal and hexagonal crystals previously dealt with are uniaxial. The straight line bisecting the angle between the optic axes (called the optic axial angle) is always an axis of minimum or maximum elasticity. The optic axial angle may have any value, but when it falls to zero the crystal becomes axial. Uniaxial crystals have been made biaxial by pressure.

**Istropic Crystals.**—The crystals of the above five systems all react with polarised light, and are said to be anisotropic, or doubly refracting. Crystals of the regular or cubic

system are symmetrical with respect to all their axes, and light travels through them with the same velocity in all directions. They are therefore always dark between crossed nicols, and are styled isotropic, or singly refracting.

**Refraction.**—When light passes from one medium to another, whether isotropic or anisotropic, it always undergoes a change of velocity, in consequence of which its rays are bent in all cases where they are not normal to the surface bounding the media. This bending, or refraction as it is called, takes place according to a definite law depending on the change in velocity which gives rise to it. Taking a perpendicular from the surface of contact of the two media, and measuring angles from it (see Fig. 3), we find that if—

$i$  = angle of incidence,

$r$  = angle of refraction,

$\frac{\sin i}{\sin r}$  = a constant, which is called the *index of refraction* when the first medium is air, and is abbreviated to I.R.

An anisotropic section has two indices of refraction, one for each component; this is called double refraction (D.R.).

Solids usually have higher refractive indices than liquids, and liquids have higher ones than gases. A ray passing from a substance having

YC, BD, EF, KG, and LH are perpendiculars to the surfaces of the glass and calcite respectively.

$i$  and  $i'$  are angles of incidence.

$r$ ,  $r'$ , and  $r''$  are angles of refraction.

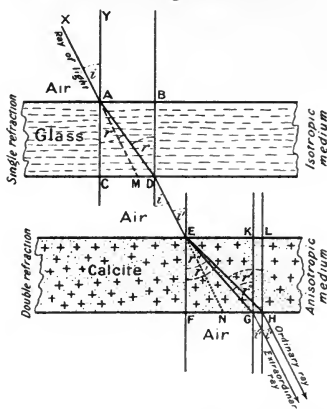


FIG. 3

$$\begin{aligned} \text{Index of Refraction} &= \frac{\sin (\angle \text{ of incidence})}{\sin (\angle \text{ of refraction})} \\ &= \frac{\sin i}{\sin r} \end{aligned}$$

In the isotropic medium (top part of the figure) there is one I.R. only:—

$$\text{I.R.} = \frac{\sin i}{\sin r} = \frac{CM}{AM} \div \frac{CD}{AD}$$

In the anisotropic medium (lower part of the figure) there are two indices of refraction, I.R. and I.R':—

$$\text{I.R.} = \frac{\sin i'}{\sin r'} = \frac{FN}{EN} \div \frac{FH}{EH}$$

$$\text{I.R.}' = \frac{\sin i'}{\sin r''} = \frac{FN}{EN} \div \frac{FG}{EG}$$

$$\text{Double Refraction} = \text{D.R.} = \text{I.R.}' - \text{I.R.}$$

For small angles  $EN = EG = EH$  nearly.

$$\begin{aligned} \therefore \text{D.R.} &= \frac{FN}{FG} - \frac{FN}{FH} = FN \left( \frac{FH - FG}{FH \times FG} \right) \\ &= FN \left( \frac{-GH}{FN \times FG} \right) \end{aligned}$$

In this case it is seen to be negative.

a lower I.R. to one having a higher is always bent towards the normal to the surface; and when emerging from such a medium it is bent away from the normal. If the angle of incidence exceeds a certain amount (critical angle), depending on the I.R. of the denser medium, it does not emerge from it at all, but is totally reflected. Hence in thin sections under the microscope, the light striking the edges of minerals of high I.R. obliquely is reflected back, making the edge of the mineral black and the interior more illuminated than it would otherwise be. With high powers, a thin line of light on the side of the mineral of higher refractive index is seen, as well as the black border, and by observing this the relative refractive indices of minerals may be judged with considerable accuracy in thin section.

**Pleochroism.**—Doubly refracting crystals may exhibit pleochroism. A pleochroic crystal shows different colours when viewed in different directions because it possesses the power of absorbing rays of different colours in a varying degree, according to the plane in which the light is polarised within the crystal. If a thin section of such a uniaxial pleochroic crystal, such as tourmaline, cut parallel to the principal axis, be rotated above the polarising nicol without the

analyser, it will be found that the colour changes, becoming darkest when the principal axis is parallel to the long diagonal of the nicol—that is, the plane of polarisation of the light. With other minerals this position may be the lightest. Sections at right angles to the optic axis are isotropic and non-pleochroic, because the light is no longer polarised within the crystal. The polarised rays in uniaxial crystals, such as tourmaline, show two colours only; such crystals are therefore “dichroic.” Since in biaxial crystals light travels with different velocities in three different directions, three colour changes may be expected. Biaxial crystals may therefore be *trichroic*.

**Identification of the Six Crystal Systems.**—The following rules will assist in the identification of the crystal system in thin sections of minerals, where the mineral is idiomorphic—*i.e.* possessing its own crystal outlines.

**CUBIC.**—Square, hexagonal, octagonal, or polygonal sections always isotropic, unless in a strained condition.

**HEXAGONAL.**—Sections of hexagonal, trigonal, or nine-angled form are isotropic, but not common; usual sections are lath-shaped, anisotropic, and give straight extinction.

**TETRAGONAL.**—Square and octagonal sections

isotropic but uncommon; lath-shaped and six-sided sections anisotropic with straight extinction.

**RHOMBIC.**—All sections anisotropic; sections parallel to any axis (usually rectangular) give straight extinction.

**MONOCLINIC.**—All sections are anisotropic; straight extinction occurs only in sections parallel to the orthodiagonal (usually rectangular). All other sections give oblique extinction.

**TRICLINIC.**—All sections are anisotropic and generally extinguish obliquely.

## CHAPTER III

### THE ACID PLUTONIC ROCKS

**Classification of Rocks.**—Rocks may be divided into :—

(1) **IGNEOUS ROCKS**, which have solidified from fusion.

(2) **SEDIMENTARY ROCKS**, which are derived from the wear and tear of the above, either directly or by the intervention of organisms. They are sometimes called *derivative*, and the term *clastic* is sometimes applied to them, because they are built up of fragments.

(3) **METAMORPHIC ROCKS**, formed by the reconstruction of other rocks, which may have been igneous, sedimentary, or metamorphic. Intense heat gives rise to chemical reconstruction (*recrystallisation*), whilst great pressures give rise to mechanical reconstruction (*dynamometamorphism*).

The igneous rocks may be divided into :—

(a) **PLUTONIC ROCKS**, which have consolidated at considerable depths in the earth's crust in large masses.

(b) HYPABYSSAL ROCKS, which form small intrusions at shallower depths in the earth's crust.

(c) VOLCANIC ROCKS, which have been extruded (*i.e.* poured out) as lavas on the earth's surface.

The igneous rocks are built up chiefly of silicates, which may be divided into :—

(1) ALUMINO-ALKALI SILICATES, comprising the *felspars* and the *felspathoids*, usually colourless, with low refractive index and in thin section low interference colours.

(2) FERROMAGNESIAN SILICATES, which form the coloured constituents of the rocks on account of the iron they contain, with high refractive index and double refraction.

The other constituents comprise :—

FREE SILICA in the form of *quartz* (rarely as *tridymite*).

FREE BASES, chiefly *iron ores* and *spinel*s.

ACCESSORY MINERALS, of which the most important are phosphates, such as *apatite*; oxides, such as *rutile*; and sulphides, such as *pyrites*.

In the following table the percentages of silica, alumina, alkalis (soda and potash taken together), lime, iron oxides ( $\text{FeO} + \text{Fe}_2\text{O}_3$ ), and magnesia are given, along with the indices of refraction and extinction angles.

**TABLE SHOWING ESSENTIAL CONSTI-**

Division	Class	Mineral	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
		Quartz	100%	0%
Alumino-alkali Silicates	Felspars	Orthoclase *	65	18
		Albite †	69	19
		Oligoclase †	62	24
		Andesine †	60	25
		Labradorite †	56 to 52	28 to 31
		Anorthite †	43	37
	Fel- spathoids	Nepheline	42	36
		Leucite	55	24
Transi- tional	Micas	Muscovite	45	38
		Biotite ‡	40	12.67
Ferromagnesian Silicates	Metasilicates, Amphi- boles and Pyroxenes	Hornblende	46	11.5
		Enstatite	60	0
		Hypersthene	55	0
		Augite	48	7
	Ortho Silicate	Olivine	43 to 39	0

\* Maximum extinction angles in sections perpendicular to the basal plane and clinopinakoid.

Where not otherwise specified, extinction angles are

# TUENTS OF ROCK-FORMING MINERALS

Na <sub>2</sub> O + K <sub>2</sub> O <sub>0</sub>	CaO	FeO + Fe <sub>2</sub> O <sub>3</sub>	MgO	I.R.	Extinction
0%	0%	0%	0%	1.55	Straight
17	0	0	0	1.52	at 3° to 7°
12	0	0	0	1.53	at less than 16°
8.7	5.3	0	0	1.54	at less than 6°
7.9	6.7	0	0	1.55	at 16° to 22°
5.7 to 4	10 to 13	0	0	1.56 to 1.57	at 27° to 45°
0	20	0	0	1.58	at over 50°
22	0	0	0	1.54	Straight
21	0	0	0	1.50	(Isotropic)
12	0	0	0	1.59	Nearly Straight
5.6	0	19	15.7	1.56	Nearly Straight
0	14	3.5	19	1.64	at 20° or less
0	0	0	40	1.66	Straight
0	0	17	28	1.70	Straight
0	21	11	13	1.72	at 54° or less
0	0	5 to 30	31 to 52	1.68	Straight

† Maximum extinction angles measured from albite twin lamellæ.

‡ Chemical composition variable, figures give a good average.  
measured from prismatic cleavage in longitudinal sections.

According to the relative proportions of these constituents, rocks may be styled :—

(1) ACID, when they contain much free quartz, only a small amount of ferro-magnesian mineral, and a predominance of aluminous-alkaline constituents rich in alkali. These rocks contain over 66 per cent. of silica.

(2) INTERMEDIATE, when quartz and compounds rich in iron are neither of them present in large amount, and aluminous-alkali silicates predominate. Silica percentage varies from 66 to 52 per cent.

(3) BASIC, when ferro-magnesian silicates, often very rich in iron, become dominant features. Silica percentage is less than 52 per cent.

(4) ULTRABASIC, when felspathic constituents are absent or unimportant, and ferro-magnesian minerals form the bulk of the rock. Iron ores and spinels are often very plentiful and characteristic. They contain less than 45 per cent. silica.

If reference be made to the Tables of Rocks in Chapter VII., it will be seen that the acid rocks are composed of minerals which have a high percentage of silica, have low extinction angles, low refractive indices, and, excepting the micas, low polarisation colours. On the other hand, the basic rocks are composed of minerals having

higher extinction angles, refractive indices, and polarisation tints than the corresponding minerals of acid rocks.

In the following chapters a typical series of rocks belonging to all these classes, ranging from acid to ultrabasic and from plutonic to volcanic, will be described with a view of indicating the methods of identification of the more important rock-forming minerals, together with the more important structural features of the igneous rocks.

**Rubislaw Granite.**—The grey granite of Rubislaw quarries, Aberdeen, is not only a typical granite in the popular sense, but shows an exceptionally wide range of mineralogical and structural features, making it a suitable starting-point for the student. A thin section of it may be conveniently examined under a 1-in. or  $\frac{3}{4}$ -in. objective. Its appearance is shown in Figs. 4 and 5. At first the analyser must be thrown out of action, and the examination conducted by natural or common light. On focusing the slide it will be seen that large areas of the field of view are grey, cloudy, or colourless, with here and there a yellow or brown patch, usually more or less lath-shaped, with ragged ends. Their outline is well marked, because they refract light more strongly than the surrounding minerals, and they contain long straight cleavage cracks. If

**Rubislaw Granite.**

*Essential minerals:*  
Biotite,  
Muscovite,  
Plagioclase,  
Orthoclase,  
Quartz,  
Microcline.  
*Accessory minerals:*  
Rutile,  
Apatite,  
Zircon.  
*Secondary minerals:*  
Kaolin,  
Muscovite.

we rotate either the slide or the polariser, we notice that the colour changes once every  $90^\circ$  from yellow to brown and brown to yellow. This is called pleochroism. Little spots may often be noticed much more pleochroic and darker

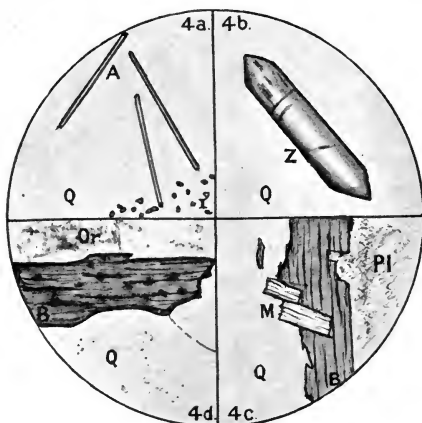


FIG. 4

4a. Apatite and gas inclusions in quartz.  $\times 270$ .

4b. Zircon in quartz.  $\times 210$ .

4c. Biotites moulding muscovite.  $\times 50$  diameters.

4d. Biotite with pleochroic halos round apatite.  $\times 35$ .

in colour than the rest. These are called pleochroic halos, and are caused by minute crystals of apatite and zircon enclosed in the mineral (see Fig. 4). If we now insert the analyser, the yellow colour gives place to brilliant pinks

and greens, which become black or extinguish if the section be placed nearly parallel to the axes of the nicols, which in a petrological microscope are indicated by cross-threads in the eyepiece. These properties are characteristic of biotite.

Among the uncoloured constituents will be seen first a mineral resembling biotite in everything except colour and pleochroism, embedded more or less in it (Fig. 4, *c.*) as if it had crystallised first and then been surrounded by the biotite. Its brilliant polarisation colours (pinks and greens) between crossed nicols enable it to be easily picked out wherever it occurs, except in very thick slides. This is muscovite.

The micas, muscovite and biotite, are surrounded and moulded by the other minerals, of which plagioclase felspar has been the first to crystallise. It is recognised in polarised light (*i.e.* crossed nicols) by its striated appearance (Pl. in Fig. 5). The light and dark bands are twin lamellæ and become black or extinguish at a small angle with the cross-threads. If the lamellæ are very sharply defined and extinguish at equal angles on opposite sides of the cross-thread, the section is at right angles to the twinning. This being so, it is worth while to measure the angle between the cross-thread and the lamellæ when extinguished, by

noting the number of degrees through which the rotating stage is turned in order to make them parallel. In the rock under consideration this will never exceed  $16^{\circ}$ , though it may be



FIG. 5.—CROSSED NICOLS

Granite, Rubislaw, Aberdeen.  $\times 45$  diameters.

- R = Rutile needles.
- Or = Orthoclase (polarises grey blue).
- Pl = Plagioclase (polarises grey blue).
- Q = Quartz (polarises white).
- M = Muscovite (polarises green and pink).
- B = Biotite (polarises green and pink).

less. The species of felspar is therefore oligoclase. By common light the plagioclase felspar shows little. Its outlines are not as conspicuous as those of biotite, since it has

only a low refractive index, but it is often cloudy within as a result of weathering. Sometimes the minute dusty decomposition products consist of kaolin (china clay). The plagioclase often shows crystal boundaries which project into the later formed minerals—*i.e.* it is idiomorphic to them. Sometimes, besides the usual or albite twin lamellæ, another set of striations is found at right angles to them known as pericline twin lamellæ.

Plagioclase usually polarises in blue grey and white tints of the 1st order in Newton's scale.

Distinguished from plagioclase chiefly by the absence of striation in polarised light is orthoclase. It is penetrated by the plagioclase, but shows good idiomorphic outlines to quartz. It is shown at Or. in Fig. 5, and is usually more or less cloudy from decomposition, usually called kaolinisation, although the decomposition products include minute flakes of muscovite as well as kaolin. Each crystal is usually divided into two halves in polarised light by twinning of the Carlsbad type. The two halves are coloured differently, the range of colours, as with plagioclase, being from blue grey to white, seldom yellow of the 1st order, though any colour may occur in thick slices.

The feldspars are embedded in a clear and

colourless base which between crossed nicols shows rather brighter tints on the average consisting of quartz. The outlines of the individual quartz grains are only visible after careful focusing, when minute interlacing hairs of the mineral rutile (R. in Fig. 5) may sometimes be noticed and strings of air and liquid bubbles. Cracks may be noticed, too, which testify to the brittleness of the quartz. Between crossed nicols it shows greyish white to yellow colours of the 1st order.

Frequently in the Rubislaw granite two other constituents are found of later consolidation than the quartz, and are found occupying the interspaces between the other minerals. The most important of these is microcline, which resembles plagioclase most but can easily be distinguished from it between crossed nicols. It has albite and pericline lamellæ crossing at right angles, but unlike those of plagioclase, which are parallel sided, those of microcline are spindle shaped, as shown in Fig. 6, giving a cross-hatched effect.

The other constituent is micropegmatite, and is a peculiar intergrowth of felspar and quartz. Its felspars and quartz have crystallised simultaneously. It is shown in Fig. 14.

Besides the above described constituents, which

form the bulk of the rock, very minute crystals are found of apatite and zircon, usually visible under a 1-in. objective, but requiring  $\frac{1}{4}$ -in. for full study. They are shown at A. and Z. in Fig. 4, *a.* and *b.* Both have very high refractive indices, so that they have deep black

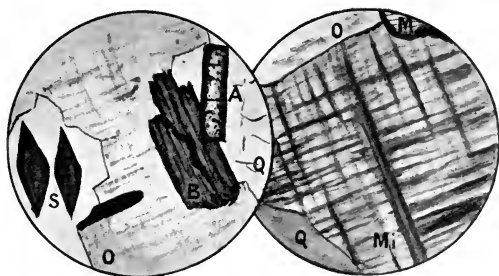


FIG. 6.

Shap granite with sphenes and apatite.  $\times 40$  diameters.

Microcline in Rubislaw granite.  $\times 40$  diameters.

S=Sphene.

O=Orthoclase (polarises grey).

A=Apatite (polarises grey).

Q=Quartz (polarises white).

Mi=Microcline (polarises grey).

M=Muscovite (polarises pink and green).

borders even when very thin. Apatite is usually in long, or rarely short, prisms with flat ends, polarises in pale grey tints, and extinguishes straight—*i.e.* parallel to the cross-thread.

Zircon also occurs in minute prisms with a very high refractive index, but the prisms do not terminate with basal planes like those

of apatite, but have obtusely pointed ends called pyramids. It extinguishes straight and polarises in very bright colours, such as pinks and greens, in minute crystals, blues, and orange reds.

Under a high power the quartz and sometimes the feldspars are seen to be filled with minute inclusions of irregular outline. Sometimes they have a very strongly marked border and consist of gas, at others they are less strongly marked and contain themselves minute gas bubbles. The bubbles often move spontaneously if very minute, and there is never more than one in each cell. The remainder of the cell must therefore be filled with liquid. In some granites cubes of rock-salt occur as well.

Viewing the rock as a whole, it will have been noticed that the most abundant constituents are quartz, orthoclase, and plagioclase, muscovite and biotite being subordinate, whilst the other constituents are present only in very small amounts.

**Shap Granite.**—Another granite may now be examined, in which, although most of the same minerals occur, their relative proportions are different and the accessory minerals such as apatite are more conspicuous and more varied. This is the well-known granite of Shap, Westmoreland.

The first thing we notice is that the biotite, instead of being clear yellow brown, is partly changed into a green substance. When only partly altered, it is still pleochroic and gives bright polarisation colours; but sometimes it will be seen to have been completely altered into a yellow to green pleochroic substance which between crossed nicols shows dull bluish grey tints or is quite opaque. This substance, chlorite, is due to the weathering of the biotite, and may be absent in very fresh specimens. The other mica, muscovite, is absent from Shap granite.

Turning to the feldspars, we notice that on the whole there are more crystals of plagioclase than orthoclase, but that some of the orthoclase crystals are very large, up to several inches in length, and are not penetrated by the other minerals. These crystals are said to be porphyritic, each crystal being termed a phenocryst. It was probably built up long before the rock was intruded into its present position. The remainder of the orthoclase bulks far less than the plagioclase and occupies the interspaces between the other minerals just as quartz does in the Rubislaw granite. The quartz is moulded by the orthoclase, but is itself penetrated by the plagioclase, which, as in most granites, can be shown to be an oligoclase.

**Shap Granite.**  
*Essential minerals:*  
 Biotite,  
 Porphyritic Orthoclase,  
 Plagioclase,  
 Quartz.  
*Accessory minerals:*  
 Apatite,  
 Zircon,  
 Spinel,  
 Magnetite,  
 Pyrites.  
*Secondary minerals:*  
 Chlorite,  
 Kaolin,  
 Muscovite.

It is, however, in its accessory minerals that the Shap granite is most noteworthy. The apatite prisms are easily seen under a 1-in. objective and cross-sections of the same, which are always hexagonal in form. The apatite has a rough surface, and by reason of its dark border seems to stand out from the slide. The cross-sections are isotropic—that is, they are dark between crossed nicols. The zircon crystals resemble those in Rubislaw granite. Their cross-sections are square and isotropic. A very characteristic accessory is *sphene*, which occurs in dark-brown wedge-shaped crystals having very strongly marked borders due to their very high refractive index. The apatite and sphene are much more abundant than the accessory minerals of Rubislaw granite. (See Fig. 6.)

Little black patches of irregular shape are seen in many slides. These are iron ores, and in Shap granite may be magnetite or pyrites. To distinguish them, a beam of light from a bull's-eye condenser should be thrown on the slide, when magnetite will appear steel grey and pyrites a brassy yellow.

Micropegmatite and microcline are usually absent from Shap granite.

A few granites contain hornblende or augite, but these minerals will be described later.

Some granites contain albite as their plagioclase felspar, and when this occurs the felspars are often found to be intergrown. The crystals of orthoclase or microcline contain thin flakes of



FIG. 7.—Microperthite.

The thin plates of plagioclase are shown cut in two directions. On the right the section shows their breadth and their alternate black and white lamellæ. On the left-hand section, cut at right angles to the former, they appear as thin lines parallel to a crystal face. Magnified about 30 diameters. Between crossed nicols.

plagioclase, which appear as bright lines when the orthoclase is extinguished. Sometimes their lamellar twinning can be recognised. Albite gives extinction angles up to  $22^\circ$  in symmetrical sections, but this property is also

shown by andesine. Microperthite, as this intergrowth is called, is shown in Fig. 7.

**Subdivision of Granites.**—Granites which contain much orthoclase usually contain muscovite and are called *potash granites*. Granites with much oligoclase, albite, and microperthite are *soda granites*. When plagioclase becomes more plentiful than orthoclase, we have *granitites*, or preferably *adamellites*, where plagioclase equals orthoclase, and *granodiorites* where plagioclase largely predominates. Altered granites may contain tourmaline, as in Luxul-lyanite, or fluorite, as in trowlesworthite.

## CHAPTER IV

### THE INTERMEDIATE AND BASIC PLUTONIC ROCKS

REPRESENTATIVES of some other families of plutonic rocks which agree with those of the granite family in structure but differ from it in mineralogical composition now claim our attention.

**Syenite.**—In the syenite of Plauen, near Dresden (see Fig. 8), it will be noticed that the coloured constituent shows no resemblance to biotite. It is pleochroic, varying from green to yellow in tint, and has a much more strongly marked border than biotite—often the surface appears quite rough. Its sections are not lath-like, like those of biotite, but more irregular; and whilst some sections show a cleavage like that of biotite, there are many which show another cleavage crossing it at an acute angle of about  $56^{\circ}$ . Between crossed nicols the polarisation colours differ markedly from those of the micas. They appear in bright reds, purples, and blues rather than the pale pinks and greens of the micas.

**Plauen Syenite.**  
*Essential minerals:*  
Hornblende,  
Orthoclase.  
*Accessory minerals:*  
Plagioclase,  
Quartz,  
Biotite,  
Apatite.  
*Secondary minerals:*  
Chlorite,  
Kaolin.

Sections with only one cleavage—*i.e.* longitudinal sections—extinguish up to  $20^\circ$  from the cleavage. This constituent is hornblende, which is typical of the great group of ferro-magnesian minerals, which are usually characterised by high

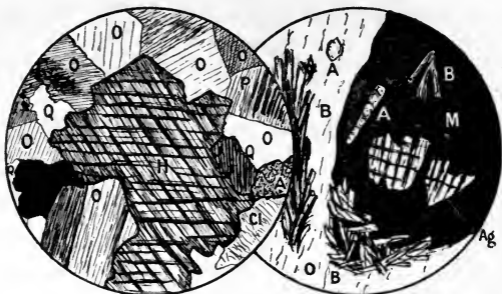


FIG. 8.

Syenite, Plauen, near Dresden.  
× 40 (crossed nicols).

Laurvigite, Laurvig, Norway.  
× 40 (common light).

H = Hornblende (polarises red and blue).

A = Apatite (polarises dark grey).

O = Orthoclase (polarises grey).

B = Biotite.

Q = Quartz (polarises yellow).

Ag = Aegirine-Augite.

P = Plagioclase (polarises grey).

M = Magnetite.

Cl = Chlorite (polarises grey blue).

refractive indices giving rise to strong outlines and rough surfaces, and by bright polarisation colours. They usually contain sufficient iron to colour them in bright greens or browns, although in thin sections some important members of the group are colourless. Biotite forms a transition

from them to the aluminous-alkali or felspathic constituents of the rocks, since it contains both constituents, and has a refractive index intermediate between that of hornblende and that of orthoclase. Like biotite, hornblende when weathered alters to green pleochroic chlorite, with weak polarisation.

Moulding the hornblende is found orthoclase, which forms the bulk of the rock, the other constituents being plagioclase and small amounts of quartz, apatite, and biotite. The plagioclase usually gives higher extinction angles than that in granites, and belongs to the species andesine, which gives angles up to  $22^{\circ}$ . It may be distinguished from albite, which gives similar extinction angles, by its refractive index, which is greater than that of quartz, whereas that of albite is less. To ascertain this, the line of junction between the felspar and quartz, or, since it has the same refractive index approximately, the Canada balsam in which the section is mounted, is focused under  $\frac{1}{4}$ -in. or higher power objective. As the objective moves downwards, the upper and under surfaces of the slide successively come into view, and a bright line of light is observed to appear first on the side of the junction where there is a higher refractive index and then on the other. The test is more delicate

Beckés test,  
for I.R.

if an iris diaphragm be placed under the stage to cut off oblique rays, and is due to Becké.

**Laurvigite.**  
*Essential*  
*minerals:*  
 Aegirine,  
 Biotite,  
 Soda felspar.  
*Accessory*  
*minerals:*  
 Magnetite,  
 Zircon.

**Laurvigite.**—Certain types of syenites may now be noticed which show the same relation to the Plauen syenite as soda granite does to potash granite. The first type is the laurvigite from Norway. The coloured constituents are three: a deep brown biotite, a brown hornblende, and a pale green mineral resembling hornblende in refractive index and polarisation tints, which is called aegirine. It differs, however, from hornblende in that its cleavages are nearly at right angles to each other, a property characteristic of all pyroxenes, and its extinction angle is less than  $5^{\circ}$ . Pyroxenes are usually non-pleochroic, except the soda pyroxenes, such as aegirine. In the rock the three coloured constituents are much intergrown with each other and with magnetite and enclose prisms of apatite (see Fig. 8). Zircon is particularly characteristic of this rock and of most syenites. The felspar is a micro- or rather crypto-perthite, in which the intergrown lamellæ of plagioclase are too fine to be resolved by the microscope. Their presence is inferred from the chemical composition of the felspar (often termed anorthoclase) and the beautiful blue iridescence which it shows by reflected light—a property termed

“Schiller,” which is always caused by minute parallel inclusions arranged along parallel planes.

**Foyaite.**—The next type is the foyaite of the Sierra de Monchique, Portugal, which contains aegirine, orthoclase, and a mineral much resembling orthoclase termed nepheline or elæolite. It is frequently cloudy from decomposition and can be recognised as follows:—The polarisation colours are less bright (*i.e.* lower) than those of orthoclase and the section extinguishes parallel to the cleavage, which is, however, sometimes difficult to trace. The only reliable test is to remove the cover-glass from the slide and place a drop of concentrated hydrochloric acid on the suspected mineral. This decomposes the nepheline into a gelatinous mass which, after washing by rinsing several times in water, can be stained by placing in a solution of magenta, which colours it pink and thus makes it more visible.

**Foyaite.**  
*Essential minerals:*  
Nepheline or  
Elæolite,  
Orthoclase,  
Aegirine.

**Ditroite.**—The third type of syenite is ditroite, from Ditró in Transylvania. It is remarkable for the abundance and variety of its feldspars, which are much intergrown and include orthoclase, oligoclase, and microcline, and for the presence of the mineral sodalite. Sodalite is easily picked out from all the other constituents, because it

**Ditroite.**  
*Essential minerals:*  
Sodalite,  
Intergrown  
Feldspars,  
Biotite.

remains dark between crossed nicols, no matter in what direction the section be cut, and in every position relative to the cross-threads. It is therefore isotropic or singly refracting in all directions, and all crystals which possess this property belong to the cubic system. Cross-sections of nepheline, apatite, and zircon are also isotropic, but all other sections of these minerals are doubly refracting or anisotropic. Sodalite moulds all the other constituents of ditroite and contains many minute inclusions. The coloured constituent is biotite and occasionally sphene. Sodalite may be distinguished from cross-sections of nepheline by its extremely low refractive index, which is considerably lower than that of Canada balsam, as may be verified by Becké's test.

**Diorite.**  
*Essential*  
*minerals:*  
 Hornblende,  
 Plagioclase.

**Diorites.**—The syenites as a whole are characterised by orthoclase felspar, and quartz is either absent or present only in insignificant amount. The diorites, on the other hand (which are now to be considered), are characterised by plagioclase felspar and hornblende or biotite. In a section of the diorite of Strathdon, Aberdeenshire (see Fig. 9), it will be noticed that hornblende is fairly abundant and shows the same features as in Plauen syenite. The plagioclase shows both albite and pericline twin

lamellæ crossing each other at right angles, and gives extinction angles ranging from  $30^{\circ}$  to  $40^{\circ}$ , and thus belongs to the species labradorite. Another characteristic property often shown is zoning. Instead of extinguishing all at once, the



FIG. 9.

Diorite, Strathdon, Aberdeen-shire.  $\times 40$  (crossed nicols).

Troctolite, Coverack, Cornwall.  $\times 40$  (crossed nicols).

H = Hornblende (polarises green, blue, and red).

P = Plagioclase, penetrated by tongues of serpentine, = S.

P = Plagioclase } (polarise grey and white).  
O = Orthoclase }

outside of the crystal is found to extinguish first as the angle between the lamellation and the cross-threads increases, and a dark zone gradually sweeps into the centre of the crystal as the stage is rotated. Sometimes the zones may be picked out by common light by means of lines of

inclusions following the crystallographic outline of the felspar. This phenomenon also occurs in the plagioclase of other rocks, such as granites. Zoned crystals are built up of concentric layers of slightly different composition. Subordinate orthoclase, magnetite, and zircon also occur.

**Basic Rocks.**—In the rocks previously considered, quartz was inconspicuous, the felspars were dominant, and the ferromagnesian silicate was hornblende or biotite, rarely a pyroxene.

In the rocks now to be described, quartz is exceedingly rare, the ferromagnesian elements become much more important than before, and iron ores are often abundant. This gives rise to a high percentage of bases as against silica in the rock analyses, so that the rocks are termed basic. Further, instead of the hornblende of the intermediate rocks (syenites and diorites), we find diallage, a peculiar variety of the pyroxene, augite. The olivine gabbro of Huntly, Aberdeenshire, will furnish many points for study, especially as it has suffered from earth movements which have brought about mineralogical changes (see Fig. 10). The ferromagnesian constituents are not highly coloured as a whole, but may be easily picked out by their strongly marked outlines and rough surfaces, and by their bright polarisation colours. The most abundant

**Olivine  
Gabbro.**  
*Essential  
minerals :*  
Diallage,  
Olivine,  
Plagioclase.  
*Secondary  
minerals :*  
Serpentine,  
Actinolite,  
Hornblende.

of them is diallage, which is pale greenish or brownish in colour and is marked with fine parallel lines (see Fig. 10). The rectangular pyroxene cleavage can sometimes be traced, and its cracks are much wider and cannot be confused

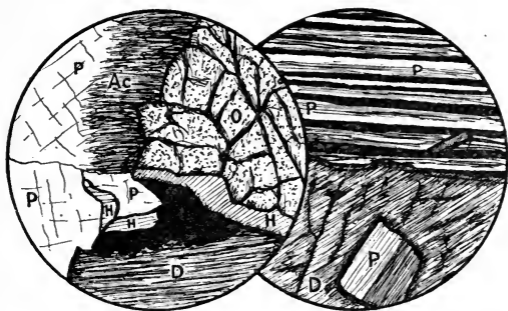


FIG. 10.—Olivine gabbro, Huntly, Aberdeenshire.

Common light.  $\times 15$ .

Crossed nicols.  $\times 15$ .

O=Olivine.

D=Diallage.

P=Plagioclase.

H=Brown to green hornblende.

Ac=Actinolite.

with the finer striation of the diallage. In sections of average thickness it polarises in red and blue colours, rarely greens. Crystals of felspar are often found partly enclosed in the diallage, and when this happens they show their proper crystal forms and are said to be idio-

morphic. Obviously, when this occurs the augite has crystallised later than the felspar. Augite gives extinction angles up to  $45^\circ$  from the trace of the cleavage.

Distinguished from diallage by the absence of striation and cleavage is olivine, which is usually colourless and has brighter polarisation tints (commonly green) than the diallage. It seldom shows any crystallographic boundaries, but occurs in irregular grains traversed by branching cracks. Its high refractive index gives it a black outline and markedly rough surface. It is very subject to alteration, and when it does so it gives rise to a pale-green fibrous mineral called serpentine, resembling chlorite but distinguished from the latter by the absence of pleochroism. The alteration commences along the cracks.

The felspar, labradorite, calls for no comment.

If the boundaries of the ferromagnesian minerals be observed closely, it will be seen that in many cases they are surrounded by a fibrous zone which is interposed between them and the felspar. These are termed reaction rims, and are attributed by some petrologists to the interaction of the two minerals at their contact under the influence of the enormous pressures of earth movements. In the case of the olivine, the zone consists of fine needles of a colourless or grass-

green mineral known as actinolite, which extinguishes about  $15^{\circ}$  from the cross-thread in the eyepiece. The diallage at its edges is altered to a yellow to brown pleochroic hornblende.

The olivine gabbro from the Cuillins, Isle of Skye, is unaltered by earth movements, and consists of pale-brown augite with diallage striation and a similar striation making an acute angle with the former known as "salite" structure, olivine granules, and labradorite. The serpentinisation of olivine may be well studied in the troctolite of Coverack, Cornwall (see Fig. 9), which consists of olivine and labradorite only. Here the olivine, by its expansion in serpentinisation, has split the felspar, the cracks in the latter being filled with serpentine, which is nearly isotropic.

**Hyperite.**—A basic rock well worth studying is the hyperite of Maud Junction, Aberdeen, N.B. It consists of accessory apatite which crystallised first, which was followed and moulded by plagioclase, which itself penetrates a mineral called hypersthene. Hypersthene belongs to the pyroxene family, but is distinguished from the augites by its pleochroism in sea-green, salmon-red, and reddish-yellow shades; its refractive index, which is higher than that of quartz but lower than that of augite; and

**Gabbro,**  
**Isle of Skye.**  
Salite  
structure.

**Troctolite.**  
*Minerals:*  
Olivine,  
Labradorite.

**Hyperite,**  
**Maud Junction.**  
*Minerals:*  
Hypersthene,  
Hornblende,  
Plagioclase,  
Quartz,  
Accessory  
Apatite.

its polarisation colours, which vary from pale yellow to orange red in good sections. It always extinguishes straight, whereas augite usually extinguishes at  $45^\circ$  from its prismatic cleavage in longitudinal sections. It has the

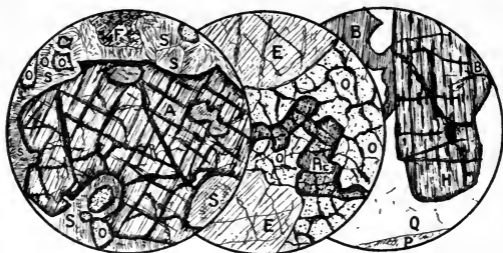


FIG. 11.

Augite picrite, Inchcolm, Firth of Forth (common light).  $\times 25$  diameters.

A = Augite.  
S = Serpentine.  
O = Olivine.  
F = Felspar.

Lherzolite, Sein Ariège, France (common light).  $\times 30$  diameters.

Pic = Picotite.  
O = Olivine.  
E = Enstatite.

Hyperite, Maud Junction, Aberdeen, N.B. (common light).  $\times 30$  diameters.

B = Biotite.  
H = Hypersthene.  
Q = Quartz.  
P = Plagioclase.

rectangular cleavage in cross-section characteristic of pyroxenes, and longitudinal sections show one cleavage parallel to the length of the crystal. But its most characteristic property are rows of rod-like inclusions, arranged parallel

to three directions in the crystal, which consist usually of iron ores. The coppery lustre, or "Schiller," of hypersthene in ordinary light is due to this cause, and the productions of such minute inclusions along parallel planes is termed "schillerisation" (see Fig. 11). The hypersthene penetrates green hornblende, the latter being moulded by biotite, and a fair amount of quartz is present as the last product of crystallisation.

**Ultrabasic Rocks.**—Certain rocks must now be referred to in which the felspars are inconspicuous (picrites) or absent (peridotites). They usually contain much olivine—in peridotites over 50 per cent.

**Augite Picrite.**—An interesting type is the augite picrite of Inchcolm, Firth of Forth, which consists of a purplish brown, slightly pleochroic augite, which encloses grains of serpentinised olivine. Serpentine derived from olivine of bright yellow, green, and blue tints occupies the interspaces between the augite individuals, which often show crystal faces. Some areas in the serpentine give bright polarisation tints and are pleochroic and contain a variety of hornblende derived from olivine. The serpentine itself gives dark blue-grey polarisation tints. Small amounts of cloudy

**Augite Picrite.**  
*Essential minerals:*  
 Olivine,  
 Augite,  
 Felspar.  
*Accessory minerals:*  
 Iron ore,  
 Biotite,  
 Apatite.  
*Secondary minerals:*  
 Serpentine  
 Olivine.

felspar, black iron ore, biotite in small flakes, and apatite are also present (see Fig. 11). The enclosure of grains of olivine in augite is an example of poecilitic structure.

**Lherzolite.**

*Minerals:*  
Diopside,  
Enstatite,  
Olivine,  
Picotite.

**Lherzolite.**—A typical peridotite is the lherzolite of Sein Ariège, France (see Fig. 11), which consists of interlocking granules of olivine and various pyroxenes. The latter comprise diopside, which is a colourless pyroxene, and enstatite. Enstatite resembles hypersthene in its properties, but is not so well coloured, so that it is colourless in thin section. Colourless sections are of course non-pleochroic. The refractive index and polarisation tints are lower than those of hypersthene. Like hypersthene, it extinguishes straight. It frequently alters to a fibrous substance known as bastite, resembling it in other microscopical properties. A very typical accessory mineral in lherzolite and other peridotites is picotite. Picotite has a very high refractive index, and hence has a very deep black border and rough surface, but between crossed nicols it remains dark for all positions of the slide—*i.e.* it is isotropic. It is usually a very dark brown colour, and occurs in granules rather than in crystals, though it is moulded by all the other constituents of the rock. It belongs to the spinel group, and

other spinels differ from it principally in colour, mode of occurrence, and chemical composition. Thus pleonaste is green and frequently occurs in polygonal crystals; chromite is darker in colour than picotite, being usually opaque in any but the thinnest slices.

In the picrites and peridotites we have the antithesis of the acid rocks; they are therefore termed ultrabasic. Instead of free quartz, we find free bases, such as the iron ores and spinels, whilst the silicates themselves are chiefly varieties of olivine which contain twice as much of the bases as the hornblendes and augites of the intermediate rocks.

## CHAPTER V

### THE HYPABYSSAL ROCKS AND THE STUDY OF THE GROUNDMASS AND PHENOCRYSTS

THE hypabyssal rocks are less coarsely crystalline than the plutonic rocks of the last two chapters, and form a perfect transition from these to the volcanic rocks, which are to be described later.

Riebeckite  
Micro-  
granite.  
*Minerals :*  
Riebeckite  
Microperthite,  
Quartz.

**Riebeckite Microgranite.** — The riebeckite microgranite of Ailsa Craig, Firth of Clyde, Scotland (see Figs. 12 and 13), may be first examined.

On examining a slide of this rock by natural light, it will be noticed that the coloured constituent is unfamiliar (see Fig. 12). It forms ragged patches of a dark blue or brown colour, and when the polariser is rotated it will be seen that it is pleochroic in blue, indigo blue (or black), and dark green shades, and that it has bright interference colours, and strongly marked boundaries, indicating high double refraction and refractive index. It has a cleavage like that of hornblende—that is, in cross-sections

two cleavages cross each other at  $124^{\circ}$ , whilst in other sections only one cleavage is seen. It will be noticed that in these latter the mineral extinguishes in polarised light when only about seven degrees from the cross-wire, thus differing

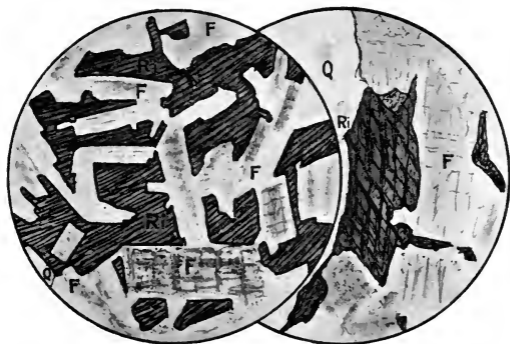


FIG. 12.—Riebeckite microgranite, Ailsa Craig, Firth of Clyde (common light).  $\times 80$  diameters.

Ri = Riebeckite (deep blue and brown).

F = Microperthitic felspar (cloudy).

Q = Quartz.

from true hornblende, whose extinction angle is as high as  $20^{\circ}$ , and from augite, where the angle may be as high as  $45^{\circ}$ . This mineral is riebeckite, and belongs to the amphibole group, of which hornblende is a characteristic member. Riebeckite differs from hornblende in containing

soda instead of lime, and its presence shows that the magma which formed this rock was rich in soda. The ragged outlines of the riebeckite crystals are due to the fact that



FIG. 13.—Riebeckite microgranite, Ailsa Craig, N.B.

Microgranitic structure (between crossed nicols).  $\times 40$  diameters.

Granophyric structure with feldspar extinguished (between crossed nicols).  $\times 60$  diameters.

Q=Quartz (polarises grey to straw yellow).

F=Felspar (polarises grey to white).

the riebeckite has crystallised around the felspars, which penetrate it in every direction.

Among the uncoloured constituents may be seen between crossed nicols fairly large crystals

of cloudy felspar, which in polarised light show the structure of microperthite already alluded to (p. 39). When nearing the position of extinction, bright lines are often seen made up of thin plates of plagioclase felspar intercalated in the orthoclase parallel to a crystal face. The weathering of the felspar has caused a rectangular patterning, which is very characteristic.

Clear, colourless, irregular grains of quartz should next be noticed. They rarely show any crystal forms, though not penetrated by the other minerals. These large quartz and felspar individuals are termed phenocrysts, being porphyritic in the same way as those in the Shap granite, and, as in the case of the latter, there is a "second generation" of smaller crystals in the groundmass. The groundmass is, however, here very fine compared with the finest grained portions of a normal granite—hence the term "microgranitic" applied to it. It consists of little rectangular crystals of orthoclase felspar imbedded in quartz, which, as in the Rubislaw granite, has been the last mineral to crystallise. Sometimes, however, neither the orthoclase nor the quartz show crystal outlines, but the quartz appears in peculiar angular pieces thickly scattered through

Microgranitic  
groundmass.

Granophytic  
groundmass.

large patches of orthoclase. Between crossed nicols all the patches of quartz throughout a considerable area extinguish together—in other words, we have here an orthoclase crystal intergrown with a quartz crystal, the two penetrating each other in a very irregular manner. They represent the consolidation of mother liquor from which the phenocrysts had crystallised, and constitute micropegmatite. The constituents solidified simultaneously, so that neither was able to develop properly its own crystal form. It is shown in Fig. 13.

**Felsites.**—We see that in this rock there are two kinds of groundmass, the “microgranitic” and the “micropegmatitic,” and the production of each is associated with peculiar conditions of cooling. Many microgranites show no micropegmatite, whilst others consist almost entirely of it. Further, in both cases the groundmass can be of any degree of fineness until it becomes too fine to be resolved by the microscope. If we take a microgranitic groundmass, we see that when the interlocking grains become so fine as to cease to be visible separately, a mottled or speckled effect will be produced between crossed nicols, because the different individuals of the groundmass extinguish at different times. This is a “felsitic” groundmass, and such rocks

are called felsites. Typical quartz felsites occur in Cornwall (see Fig. 15) which contain phenocrysts of quartz showing hexagonal outlines and orthoclase feldspar. A colourless to brown pleochroic mineral forms lath-shaped and sub-triangular sections, the former showing brilliant polarisation colours, the latter more or less isotropic. This is tourmaline, which may be distinguished from biotite, which it sometimes resembles, by the absence of cleavage parallel to the length of the laths. The colour, usually yellowish brown, varies from place to place in the same crystal, and in triangular sections is often arranged in zones. The rectangular sections often show rough transverse cracks, and the outlines are strong on account of the high refractive index. It extinguishes straight.

**Quartz Felsite.**  
Minerals :  
Quartz,  
Orthoclase,  
Tourmaline.

**Granophyre.**—Among the micropegmatitic rocks may be taken as a type the augite granophyre of the Isle of Muck, Hebrides (Fig. 14). The micropegmatite which forms the groundmass is often very coarse, and in it are embedded phenocrysts of orthoclase quartz and augite. The augite is pale green or colourless, and shows no diallagic striation like the augite of gabbros, but only rough cleavage cracks. When two cleavages occur, they cross almost at right angles. The augite is moulded by the

**Augite Granophyre.**  
Augite,  
Orthoclase,  
Micro-  
pegmatite.

felspar, and the latter by the quartz, as in granites, but most of the felspar is intergrown with the quartz as micropegmatite. The felspar of the micropegmatite is usually in optical continuity with that of the phenocrysts—that is, they extinguish together. Where the inter-

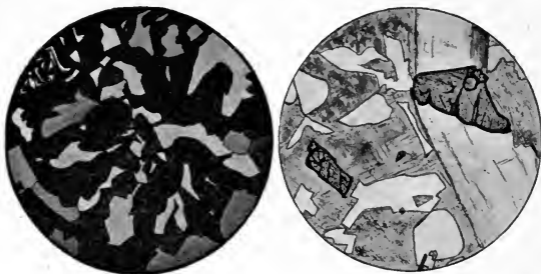


FIG. 14.

Micropegmatite in augite granophyre, I. of Muck. Seen between crossed nicols and magnified about 20 diameters. The quartz is light and the felspar black.

Another part of the same slide, with ordinary light, showing augite with black borders and rough surface, and orthoclase felspar (cloudy) embedded in micropegmatite. Magnified 20 diameters.

growth becomes finer, it is often seen to radiate around the centres, the micropegmatite about each centre containing sectors of felspar coming from different phenocrysts and hence extinguishing differently. In many granophyres the growth may be seen to be still finer, when the radial arrangement becomes more marked, so

that it takes the form of spheres, called pseudo-spherulites, made up of conical bundles of felspar fibres intergrown with quartz in micropegmatitic fashion. Between crossed nicols those fibres nearly parallel to the cross-threads are extinguished so that a black cross is produced. When the constituent fibres cease to be distinguishable except by very high powers, we get true spherulites, which, however, in many cases consist of felspar fibres only (see Fig. 19, c).

**Markfieldites.**—The above rocks are the fine-grained or hypabyssal representatives of the granites, but hypabyssal representatives of all the other plutonic rocks also occur. Those corresponding to the syenites are called porphyries, those of dioritic composition porphyrites. An important type is the dioritic granophyre, or markfieldite, in which the base is micropegmatite. A good example is the bronzite markfieldite of Penmaenmawr (coarse-grained variety), which contains beautiful micropegmatite in which are embedded pale green augite, a rhombic pyroxene intermediate between enstatite and hypersthene called bronzite, often intergrown with the augite, large crystals of plagioclase, usually much decomposed, iron ores, and fine needles of apatite. The iron ore presents a peculiarity we have not hitherto met with (see Fig. 15, right-hand side).

Pseudo-spherulites.

**Bronzite  
Markfieldite.**  
*Minerals:*  
Augite,  
Bronzite,  
Plagioclase,  
Micro-  
pegmatite,  
Ilmenite,  
Apatite.

Like magnetite, it is black and opaque by transmitted light, but by reflected light it shows greyish white patches, usually arranged along lines intersecting at about  $60^\circ$ . These patches are of a titanium-bearing mineral, leucoxene,

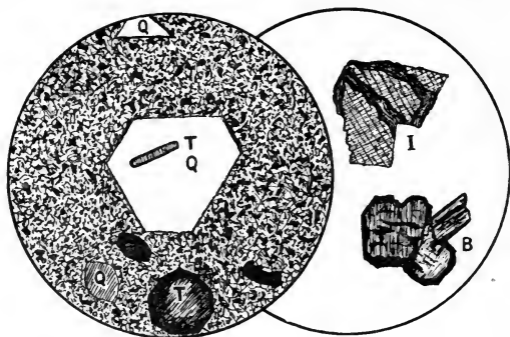


FIG. 15.

Quartz felsite, Cornwall.  $\times 30$   
diameters.

Q = Quartz.

T = Tourmaline (brown) in felsitic groundmass.

I = Ilmenite (by reflected light).  
 $\times 40$  diameters.

B = Bronzite from Markfieldite, Penmaenmawr (by transmitted light).  $\times 60$  diameters.

formed from the alteration of an iron ore containing titanium known as ilmenite. Ilmenite differs from magnetite (which being cubic gives square sections) in being hexagonal in crystallisation, though both minerals frequently occur in irregular grains. Penetrating the iron ore we

find the pyroxenes, which are green in colour. The rhombic pyroxene is somewhat pleochroic in green and reddish shades and gives straight extinction, whilst the augite is non-pleochroic and extinguishes at nearly  $45^{\circ}$  from the cross-threads. The rhombic pyroxene shows every stage of alteration from a perfectly fresh condition to the fibrous substance replacing it called bastite. The plagioclase is usually too much decomposed to show twin lamellation, but the cloudiness caused by this decomposition enables its large crystals to be easily picked out. The orthoclase intergrown as micropegmatite is much clearer than the plagioclase. The apatite builds both stout prisms and fine needles with high refractive index and rough surface penetrating all the other minerals. Its dull greyish-blue polarisation colours also distinguish it easily from other minerals.

The typical markfieldite is quarried at Markfield and Groby, in Leicestershire. It is locally known as "syenite," but closely resembles the Penmaenmawr rock, except that instead of pyroxenes it has hornblende. The Groby "syenite" shows abundant plagioclase with twin lamellation and particularly fine micropegmatite. Associated with the hornblende are granules of epidote, a colourless to pale yellow pleochroic mineral

with high refractive index and brilliant polarisation colours. It has two cleavages intersecting at about  $115^{\circ}$ .

**Dolerites.**—The hypabyssal representatives



FIG. 16.—Ophitic dolerite, Pouk Hill, Walsall (natural light).  $\times 40$  diameters.

A = Augite (polarises red or blue).

O = Olivine (polarises green).

S = Serpentine.

F = Felspar (polarises grey).

M = Magnetite.

**Pouk Hill  
Dolerite.**  
*Minerals:*  
Labradorite,  
Augite,  
Olivine,  
Iron ore.

of the gabbros are called “dolerites.” A typical occurrence is that of Pouk Hill, Walsall, Staffordshire (see Fig. 16), which consists of laths of labradorite felspar usually fresh and showing lamellar twinning which penetrate and have

therefore crystallised before the other constituents. In between the felspar crystals lie patches of augite, olivine, and iron ore. The augite is pale purplish brown in colour and faintly pleochroic. It builds up large crystals enclosing the felspar laths, so that in section each crystal often appears only in isolated patches. That these patches all belong to the same crystal is frequently shown by the fact that the cleavages run parallel throughout a considerable area, in which all the patches of augite extinguish simultaneously. The olivine is often partly altered to serpentine along the cracks and at the margins. Sometimes it appears intergrown with the augite. The magnetite often shows square sections, but is penetrated by the felspar laths. The big augite crystals in this rock function as groundmass, and are termed "ophitic." The ophitic structure is very common in dolerites, and shows that the rock did not move during consolidation. When movement has occurred during the solidification of a dolerite, the augite takes the form of granules moulding the other constituents instead of ophitic plates. (See Granulitic Basalts, p. 84.)

**Epidiorite.**—Some dolerites, especially the more ancient ones, have suffered from earth movements since they consolidated. When subjected to the stresses thus caused, augite

usually changes into hornblende, usually a pale green fibrous variety termed uralite, which shows the outward form of augite and the internal structure (cleavages and pleochroism) of hornblende. A good example is the Scourie Dyke from Sutherland, N.B. (see Fig. 17), in which

**Scourie  
Dyke.**  
*Minerals:*  
Secondary  
Hornblende,  
Plagioclase.

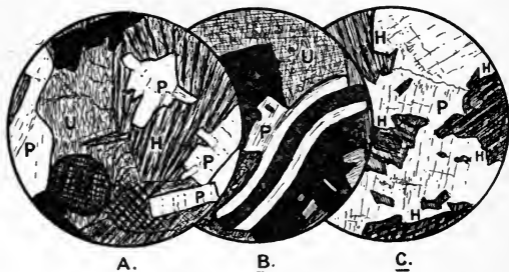


FIG. 17.—Scourie Dyke, Scourie, Sutherland.  $\times 25$  diameters.

A = Uralitised dolerite (common light).

B = Uralitised dolerite (crossed nicols).

C = Epidiorite (common light).

P = Plagioclase.

A = Augite.

U = Uralite.

H = Recrystallised hornblende.

various stages in the alteration may be seen. The alteration of the augite commences from the outside, so that unchanged kernels of augite remain inside (Fig. 17 A.). The plagioclase crystals also bear witness to the stress of earth movements, for many of them are noticeably bent (see Fig. 17 B.). In its most crushed parts the

rock shows complete recrystallisation, the minerals having been broken up completely. Instead of uralite we have a very pleochroic bluish-green hornblende in very ragged crystals, whilst the felspar is in irregular patches and has lost all resemblance to the idiomorphic laths so characteristic of dolerites (see Fig. 17 c.).

**Teschenite.**—Some dolerites show a “granulitic” structure similar to that which will be described in basalts in the next chapter. An interesting type allied to the dolerites is the augite teschenite of Gullane, Haddingtonshire. The earliest formed constituent is apatite, which was followed by abundant olivine, often largely converted into yellowish-green serpentine, moulded by rather dusky plagioclase. Ophitic augite encloses the plagioclase and moulds granules of iron ore (ilmenite), the interspaces between the constituents being occupied by a colourless base which is isotropic. This base is not glass, but analcime, which crystallises in the cubic system; and is sometimes original, but sometimes secondary after nepheline.

**Augite**  
**Teschenite.**  
*Minerals:*  
Apatite,  
Olivine,  
Plagioclase,  
Augite,  
Ilmenite,  
Analcime.

**Lamprophyre.**—A peculiar type of hypabyssal rock must now be mentioned, to which the term lamprophyre is applied. A good example is the mica lamprophyre or minette, of Swindale Beck, near Appleby, Westmoreland,

**Minette.**  
*Minerals:*  
 Orthoclase,  
 Biotite,  
 Calcite,  
 Pyrites.

(Fig. 18). It consists of a rich brown-coloured groundmass composed of stained and decomposed orthoclase, in which is set numerous laths of biotite of various sizes, some large others small. The biotite is light brown in colour, the



FIG. 18.—Mica lamprophyre, Swindale Beck, near Appleby, Westmoreland.  $\times 50$  diameters.

Q = Quartz (polarises white).      F = Felspar (cloudy).  
 C = Calcite.      B = Biotite.      P = Pyrites.

interior being lighter than the edges ; sometimes it is nearly colourless. This bleaching of the biotite is due to the removal of its iron by weathering. The process may often be seen to have gone much further, so that some laths are

largely changed into a colourless to grey substance which shows between crossed nicols very faint colours—chiefly pinks and greens. This is calcite, which also frequently occurs in the groundmass. Other properties of calcite are strong cleavages intersecting at an acute angle in three directions and lamellar twinning. The iron ore which occurs sporadically deserves notice, as it is pyrites, not magnetite or ilmenite. The pyrites is easily distinguished by its brassy lustre when viewed by reflected light. Small prisms of apatite occur in the groundmass.

## CHAPTER VI

### THE VOLCANIC ROCKS

VOLCANIC rocks present a few minerals only which are practically absent from igneous rocks ; but their greatest interest lies in their structure, which usually testifies to their extrusion or pouring out over the surface of the earth. They are divided into lavas graduating into the hypabyssal rocks which fill the channels which fed the volcanic centres, and tuffs which are the result of the cementing and hardening of the volcanic ash produced by paroxysmal eruptions.

Every hypabyssal, and therefore every plutonic class of rocks, has its representative in the volcanic series.

**Rhyolite.**  
*Minerals :*  
Quartz,  
Felspar,  
embedded in  
glass.

**Rhyolites.**—The rhyolites or liparites correspond to the granites, and will be described first. They may conveniently be considered as (1) the newer rhyolites, which are usually in a fresh condition, and (2) the older rhyolites, which have suffered various alterations, such as devitri-fication, silicification, &c. The newer rhyolites are typically characterised by a large amount of

glass, which is colourless or pale green or brown and is always isotropic. The glass may occur in any proportion; very rarely it occurs in small amount in the interspaces between the crystals, this type being known as nevadite. On the other hand, the rock may be almost entirely glassy, such rocks being termed "obsidians." Often the glass contains abundant minute embryo crystals termed microlites and crystallites, and the rock, from its peculiar lustre on fracture, is termed "pitchstone." When these embryo crystals react with polarised light they are termed microlites, but very often they do not, and show no crystalline form (Fig. 19, *a*). In their simplest form they are then globular, but the globules (globulites) may be aggregated together into rods (belonites) or long twisted hairs (trichites). The microlites often form beautiful arborescent groups as in the pitchstone of Corriegills, Arran (Fig. 19, *b*). Usually, in both pitchstones and obsidians we find a number of crystals, either of quartz or orthoclase, or both, rarely albite or oligoclase. When the orthoclase crystals become abundant we have typical rhyolites. The quartz crystals are often rounded and have long inlets of the glassy base. The feldspars usually appear as short laths often with rough transverse cracks, this variety of orthoclase being distinguished as

**Obsidian,**  
chiefly glass.

**Pitchstone.**  
Crystallites  
and Micro-  
lites.

sanidine. Ferromagnesian minerals are usually inconspicuous, and when present consist of biotite augite, or hornblende. Many pitchstones are of hypabyssal origin; indeed, nearly all the types

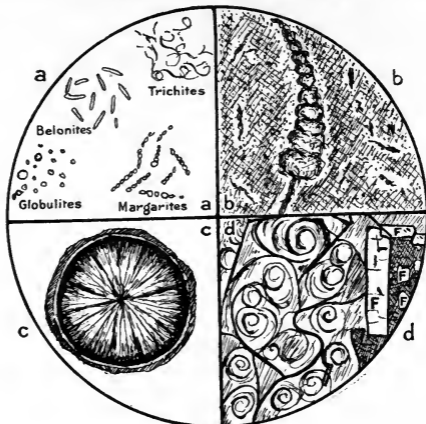


FIG. 19.

(Common light.)

a = Crystallites.  $\times$  about 200 diameters.b = Feathery microlites.  $\times$  100 diameters.c = Spherulite from obsidian, Isle of Lipari.  $\times$  40 diameters.d = Perlitic pitchstone, Ponza Isles.  $\times$  40 diameters.

F = Sanidine.

of volcanic rocks may occur as small intrusions as well as lava flows.

**Pantellerite.**—Though flow may take place during the consolidation of a small intrusion

(dyke or sill) of igneous rocks, it is much more characteristic of lavas, especially those of acid condition, whose viscosity in the molten state lends itself peculiarly well to the preservation of the lines of flow. Even in a purely glassy rock flow structure may be shown by bands of a darker coloured glass, which may be straight but are more often wavy or contorted. When microlites occur they are usually found to be drawn into parallelism with the lines of flow. Both features are shown by the glassy pantellerite from the Isle of Pantellaria, near Italy (Frontispiece). Here the microlites consist partly of aegirine, a green pleochroic mineral which shows on cross-section the rectangular cleavage of a pyroxene and an extinction angle of less than  $5^\circ$ , a reddish brown to black pleochroic mineral giving hexagonal and lath-shaped sections which consist of cossyrite.

**Pantellerite.**

*Minerals:*

Aegirine,

Cossyrite.

**Spherulites.**—Spherulites have been mentioned on p. 63. They are peculiarly characteristic of many rhyolitic rocks. Spherulites frequently grow around a small crystal, and are characterised by their fibrous radial structure giving a black cross between crossed nicols. A good rock to study is the spherulitic obsidian of the Isle of Lipari (Fig. 19, c), where the spherulites are brown and embedded in a glassy base.

**Perlitic Pitchstone.**—Perlitic structure, which is due to the contraction on the cooling of the glassy rock, is characteristic, and may be studied in the perlitic pitchstone of the Ponza Isles (Fig. 19, *d*). It consists of a series of spiral cracks which cause the rock in hand specimens to break up into little spheres like pearls, hence the name. Around these spiral cracks is a certain amount of strain in the glass, which in thick sections causes double refraction, and consequently polarisation colours appear between crossed nicols outlining the cracks.

**Devitrification.**—The older rhyolites differ from the newer only in that they are less fresh and have been altered by weathering, and the devitrification that attacks all glass in time. Glass is not theoretically stable, and accordingly we find in all these older rhyolites that the once glassy groundmass has become cryptocrystalline and gives a flecked or dappled appearance between crossed nicols. Many of the so-called felsites of Caernarvonshire are really rhyolites, and their flow structure, which is well marked, is brought out by the parallel disposition of lenticles of quartz. Much of the felspar is plagioclase, and the ferromagnesian minerals, which are very scarce, are always represented by chloritic pseudomorphs.

**Trachytes.**—Let us now turn to the volcanic representatives of the syenites, which are termed trachytes. As might be expected, the chief constituent is orthoclase felspar, which occurs in two forms, viz., as microlites and as phenocrysts. The microlites are usually packed together with a parallel arrangement, which testifies to the direction of flow and is so characteristic of the group that it is termed the *trachytic* groundmass. In it are embedded the phenocrysts, which may be orthoclase, augite, hornblende, or biotite. In trachytes orthoclase usually is clear, often untwinned, and shows the rough transverse cracks that characterise sanidine. In some trachytes—*e.g.* the augite trachyte of Peppereraig Hills, near Haddington (Fig. 20)—the orthoclase appears in masses packed together showing idiomorphic boundaries externally but irregular interpenetrating edges inside, reminding one of the granular structure of a plutonic rock. There is little doubt that these “*glomeroporphyritic*” aggregates have been formed in the deep-seated reservoirs from which the lava came.

**Peppercraig Trachyte.**

*Minerals:*  
Augite,  
Orthoclase.

**Phonolite.**—Corresponding to the nepheline syenites are the phonolites—*e.g.* the phonolite of Wolf Rock, Cornwall (Fig. 20). Here we may note that the nepheline, no longer the

**Phonolite.**

*Minerals:*  
Sanidine,  
Nepheline,  
Nosean,  
Aegirine.

massive variety elaeolite, shows crystal outlines, square in longitudinal sections, hexagonal in cross-sections, the latter isotropic. The isotropic mineral in polygonal crystals with strongly marked zoning is "nosean." Sometimes the

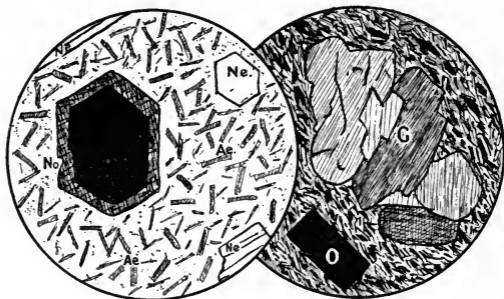


FIG. 20.

Phonolite, Wolf Rock, Cornwall (natural light).  $\times 40$  diameters.

No=Nosean.  
Ne=Nepheline.  
Ae=Aegirine.

Augite trachyte, Pepperraig Hills, near Haddington (crossed nicols).  $\times 40$  diameters.

G=Glomeroporphyritic aggregate of orthoclase.  
O=Orthoclase phenocryst.

crystal of nosean is dark at the edge and light inside, sometimes *vice versa*. When coloured at all, it is pale blue. The sanidine phenocrysts show the usual transverse cracks. The ferromagnesian constituent is aegirine, which shows lath-shaped sections with characteristic green

colour, slight pleochroism, and very low extinction angle.

**Leucitophyre.** — Allied to the phonolites are the leucitophyres, which are characterised by the mineral leucite. A typical leucitophyre from Rieden, The Eifel, consists of phenocrysts of leucite, dark-bordered nosean, and green aegirine-augite, embedded in a groundmass of microlites of aegirine-augite, nepheline, and sanidine, sometimes with a second generation of leucite. The leucite crystallises in the cubic system in icositetrahedra, which give polygonal sections which in small crystals are isotropic, but in large crystals show faint grey polarisation tints and a complicated series of twin lamellæ resembling those of microcline (see Fig. 21).

**Leucitophyre.**  
*Minerals:*  
Leucite,  
Nosean,  
Aegirine,  
Nepheline,  
Sanidine.

**Dacite.** — The volcanic representatives of the diorites are the andesites, the granodiorites being represented by the dacites. Taking a dacite from Transylvania (Fig. 21) as a type, it will be seen that the groundmass is glassy, as in the rhyolites, containing granules of quartz and patches of chlorites resulting from the decay of biotite. The phenocrysts consist of large crystals of plagioclase, and smaller ones of biotite and quartz, the latter not usually showing crystal outlines. The biotite is much chloritised

**Dacite.**  
*Minerals:*  
Plagioclase,  
Resorbed  
Biotite,  
Quartz.

and shows strongly marked black borders in common light, which resolve themselves on careful scrutiny into granules of magnetite. This "resorbtion" border of magnetite is due to the corrosion of the biotite by the molten part of the lava after eruption. The biotite was

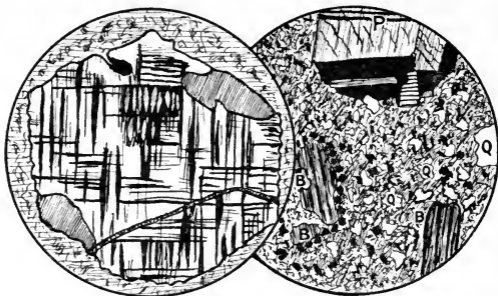


FIG. 21.

Leucite in leucitophyre, Rieden,  
The Eifel (crossed nicols).  
× 40 diameters.

Dacite, Transylvania (crossed  
nicols). × 40 diameters.

P=Plagioclase.

B=Biotite with resorbtion  
border of magnetite.

Q=Quartz.

probably formed under high pressure, and was not stable in presence of the molten lava at high temperatures and low pressures.

**Andesites.**—The andesites may be divided into two groups:—

1. The hornblende mica andesites, graduating into the dacites.

2. The pyroxene andesites, graduating into the basalts.

The hornblende andesite of Mount Shasta, California (Fig. 22), is a typical example of the first kind. It consists of phenocrysts of zoned labradorite and brown hornblende. The latter shows in cross-section diamond-shaped and six-sided prisms, with good cleavages parallel to the prism faces, which meet at  $124^\circ$ , having dark "resorption" borders of magnetite, due to corrosion by the magma and inlets of the groundmass from the same cause. Magnetite is a plentiful accessory, together with minute prisms of apatite. The groundmass consists of innumerable felspar laths and microlites "felted" together, the interspaces being filled with glass. This is the "*hyalopilitic*" or "*andesitic*" groundmass. When glass is absent, the term "*pilotaxitic*" is used instead. Often the felspar microlites have a parallel arrangement giving rise to a flow structure.

The pyroxene andesites may contain either a rhombic (enstatite) or a monoclinic (augite) pyroxene, or both, such as the enstatite andesites of the Cheviots (Fig. 22). These contain phenocrysts of labradorite, of enstatite, and augite, the two latter often intergrown. The pyroxenes usually show octagonal sections

**Mt. Shasta  
Andesite.**  
*Minerals:*  
Zoned  
Labradorite,  
Resorbed  
Hornblende.

**Enstatite  
Andesite.**  
*Minerals:*  
Labradorite,  
Enstatite,  
Augite.

with a more or less well-developed rectangular cleavage. The enstatite may be distinguished from the augite by its slight pleochroism and lower polarisation tints. The groundmass is hyalopilitic.

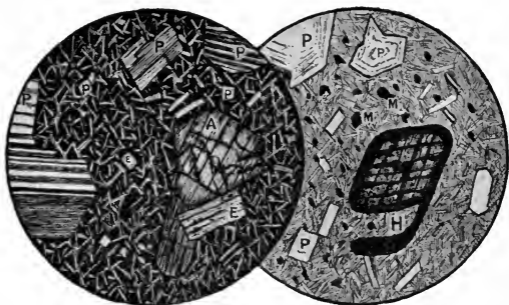


FIG. 22.

Enstatite andesite, Cheviots  
(crossed nicols).  $\times 40$  dia-  
meters.

Hornblende andesite, Mt. Shasta,  
California (natural light).  
 $\times 30$  diameters.

P=Plagioclase (polarises grey  
blue).  
A=Augite (polarises red and  
blue).  
E=Enstatite (polarises yellow).  
In andesitic groundmass.

H=Hornblende with resorb-  
tion border and corrosion.  
P=Zoned plagioclase.  
M=Magnetite.

**Basalts.**—Corresponding to the gabbros are the basalts, which vary from almost wholly glassy to almost wholly crystalline. The glassy types are rare and are called tachylytes. An interesting tachylyte comes from Hawaii, Sandwich Isles,

which consists chiefly of a brown glass in which are embedded small crystals and crystallites of augite and olivine. These show peculiar forked terminations due to the inability of the diffusion currents in the solidifying rock to feed the less

**Tachylyte.**  
Chiefly glass.

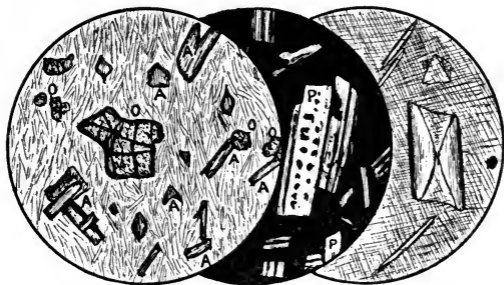


FIG. 23.

Olivine basalt, near Naples (common light).  $\times 30$  diameters.

O = Olivine.  
A = Augite.

In pilotaxitic groundmass of felspar laths.

Basalt, Forfarshire (crossed nicols).  $\times 30$  diameters.

P = Plagioclase phenocryst with inlets of glass.

Tachylyte, Hawaii.  $\times 30$  diameters. Embryo crystals of augite embedded in a glass.

accessible parts of the crystal. For the same reason the crystals tend to be long and needle shaped (Fig. 23).

Most basalts containing a notable amount of glass are much more abundantly porphyritic,

**Porphyritic Basalts.**

*Minerals:*  
Plagioclase,  
Augite,  
Olivine.

such as the basalt from Forfarshire shown in Fig. 23, where the crystals consist of labradorite with inlets of the glassy groundmass and augite. Another similar type is the basalt from the Lion's Haunch, Arthur's Seat, Edinburgh, which contains plagioclase, both as phenocrysts and as microlites, and crystals of augite and olivine, the latter often serpentinised along the cracks. An increase in the number of microlites in the groundmass tends to give a "*pilotaxitic*" structure, well shown in the olivine basalt, near Naples, Italy (Fig. 23), where the parallel disposition of the microlites gives a marked flow structure. The augite crystals give pale green lath-shaped and square sections with high extinction angle (over  $40^\circ$ ), whilst the olivines are granular and cracked with incipient serpentinisation.

**Granulitic Basalts.**

*Minerals:*  
Olivine,  
Augite,  
Labradorite.

**Granulitic Basalts.**—Very often, however, augite, as well as felspar, is an important constituent of the groundmass, and then we get the two types granulitic and ophitic basalts. The ophitic structure, which is more characteristic of dolerites than basalts, has already been described (page 67). A typical granulitic basalt is that of the Giant's Causeway, Ireland, which consists of a few felspar phenocrysts scattered in a base composed chiefly of laths of plagioclase, the inter-

spaces between them being occupied by granules of augite and olivine. Another typical granulitic basalt is that of the Summit Rock, Arthur's Seat, Edinburgh, which consists of phenocrysts

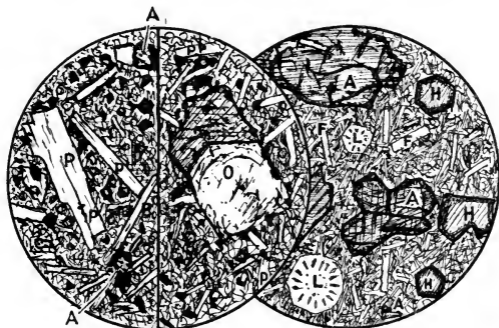


FIG. 24.

Granulitic basalt, Summit Rock,  
Arthur's Seat, Edinburgh.  
× 50 diameters.

P = Plagioclase (polarises grey  
blue).

A = Augite (polarises orange  
red).

O = Olivine in glassy base (pale  
green, serpentinised).

Häyine leucite tephrite, Monte  
Vulture, Italy. × 40 dia-  
meters.

H = Häyine (pale blue).

L = Leucite.

A = Augite (green).

F = Felspar.

of partly serpentinised olivine in a "granulitic" groundmass composed of striated labradorite laths with interstitial augite granules and colourless to pinkish glass (see Fig. 24). The olivine phenocrysts are often idiomorphic, and are then

six-sided in section, extinguishing parallel to their length. Besides serpentinisation they sometimes show alteration at the edges to a deep red iron oxide. Grains and crystals of magnetite are abundant in the groundmass.

**Felspathoidal Basalts.**—Corresponding to the phonolites are the tephrites (nepheline-bearing basalts) and basanites (nepheline-bearing olivine basalts). The nepheline may be partly or wholly replaced by leucite. The h  uyne leucite tephrite of Monte Vulture, Italy, for example, consists of phenocrysts of green aegirine augite, leucite, and h  uyne, a mineral resembling nosean but containing lime instead of soda. The leucite crystals are smaller than those of the Rieden leucitophyre, and do not show the twinning but are quite isotropic. They may be distinguished, however, by their inclusions (see Fig. 24), which are arranged regularly, either radially or parallel to the crystal faces. The h  uyne crystals are also cubic and isotropic. They are pale blue and zoned, the edge of the crystal usually being darker than the centre. The groundmass is composed of plagioclase, magnetite, and glass.

**Melilite Basalt.**—Attention must now be called to the melilite basalts, such as the melilite basalt of the Spiegel River Valley, Cape Colony

**Tephrite,  
Mt. Vulture.**  
*Minerals:*  
H  uyne,  
Leucite,  
Aegirine  
Augite,  
Plagioclase,  
Magnetite,  
Glass.

(Fig. 25). It consists of phenocrysts of fresh olivine set in a fine-grained groundmass of augite, magnetite, melilite, and perovskite. The melilite occurs in laths having a slight yellowish tinge, which give straight extinction and low polarisation colours, usually a deep indigo blue. Under

**Melilite Basalt.**  
*Minerals:*  
 Olivine,  
 Augite,  
 Melilite,  
 Magnetite,  
 Perovskite.

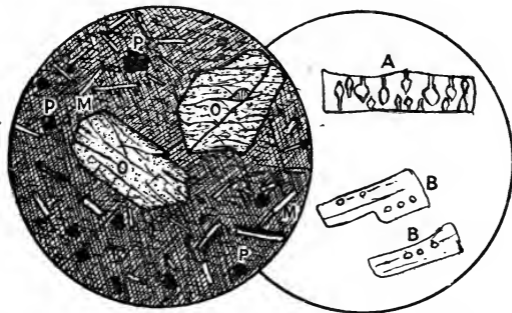


FIG. 25.—Melilite basalt, Spiegel River Valley, Cape Colony.  
 × 40 diameters.

O = Olivine with marked cleavage.

M = Melilite (yellow laths).

P = Perovskite (dark cubes).

A = Peg-structure (after Hatch).

B = Incipient peg-structure in melilite in basalt, Spiegel River Valley.

a high power, say  $\frac{1}{4}$  inch, small spherical inclusions may be noted in the melilite. In some melilite basalts these inclusions are very numerous and cause a peculiar transverse striation termed peg-structure, from the resemblance of the inclusions to little pegs. Associated with

the melilite are purplish brown grains giving polyhedral outlines which consist of the cubic mineral perovskite. They have a very high refractive index, and consequently if very small appear almost opaque.

**Limburgite.**  
*Minerals:*  
Olivine,  
Augite,  
Magnetite.

**Limburgite.**—An extreme type of basalt is known in which the felspathic element appears to be altogether wanting. These, called augites when olivine is absent, and limburgites when it is present, consist of augite, often olivine, and magnetite crystals embedded in an isotropic brownish glass with abundant black hairs (trichites) of magnetite. Taking the limburgite of Limburg, Kaiserthul (Fig. 26), as a type, it may be noticed that the olivine is much altered at the edges into brown limonite. The olivine, it should be specially noted, is idiomorphic, occurring in six-sided crystals extinguishing parallel to their length.

**Tuffs.**—The pyroclastic rocks or tuffs formed by the explosive outburst of volcanoes contain the same minerals as the lavas, from which they are derived, with, however, usually a greater proportion of glass. The latter is usually full of steam cavities, which cause the broken fragments of it to assume concave outlines which are highly characteristic. The smaller fragments are usually of glass or devitrified glass, and often laminated.

The crystal fragments tend to stand at right angles to this lamination, since they have usually dropped in from above. There is usually an extraneous cement, in which the fragments are set. This cement may be of cryptocrystalline silica, giving a dappled effect between crossed

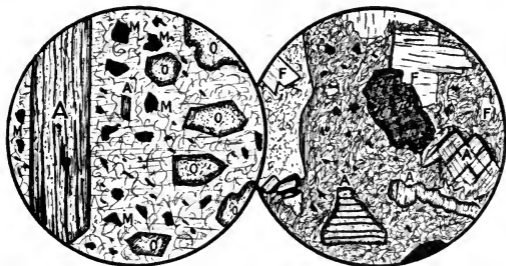


FIG. 26.

Limburgite, Limburg, Kaiserthul (common light).  $\times 35$  diameters.

A = Augite.

O = Olivine.

M = Magnetite in a groundmass of glass and trichites.

Trachyte tuff, Naples, Italy (common light).  $\times 35$  diameters.

A = Fragments of augite.

F = Felspar, and

Lapilli embedded in a matrix of glass fragments cemented together.

nicols, or of calcite. The latter is very frequent in basic tuffs, and may be easily recognised by its mosaic of interlocking grains with three cleavages parallel to the faces of the rhombohedron, lamellar twinning, and very high polarisation colours, usually having an iridescent pinkish-grey appearance.

**Trachyte  
Tuff,**  
Naples, Italy.

The trachyte tuff shown in Fig. 26, as its name implies, is a pyroclastic rock with the composition of a trachyte. The lapilli (= little stones), consisting of trachyte and broken crystals of colourless augite and orthoclase felspar, lie in a matrix of minute fragments of crystals and glass cemented together.

## CHAPTER VII

### A SYNOPSIS OF THE IGNEOUS ROCKS

#### A. Plutonic Rocks.

**Structure.**—*Granitic*—*i.e.* composed of coarse and equal-sized grains interlocking with each other. Most types are non-porphyrific. All are holocrystalline.

#### 1. The Acid Rocks, often known as the *Granite Family*.

**Minerals.**—Orthoclase or microcline, oligoclase or albite, quartz and biotite, occasionally replaced by hornblende or augite.

**Types.**—POTASH GRANITE, where *orthoclase* predominates.

SODA GRANITE, where *albite* or *perthite* predominates.

GRANODIORITE, where *oligoclase* or *andesine* predominates.

ADAMELLITE, where *plagioclase* and *orthoclase* are present in equal proportions.

## 2. The Intermediate Rocks, including the *Syenite* and *Diorite Families*.

**Minerals.**—Orthoclase or albite, or andesine, or labradorite, hornblende or augite, or biotite, and rarely quartz.

**Types.**—POTASH SYENITE, where *orthoclase* predominates.

SODA SYENITE, where *albite* or *perthite* predominates.

NEPHELINE SYENITE, where *nepheline* replaces orthoclase.

SODALITE SYENITE, where *sodalite* occurs.

DIORITES, where *andesine* or *labradorite* predominates.

MONZONITES, where *orthoclase* and *plagioclase* are present in equal proportions.

## 3. The Basic Rocks.

**Minerals.**—Orthoclase, plagioclase, augite, olivine, hornblende, biotite, hypersthene, and rarely quartz.

**Types.**—SHONKINITE, where *orthoclase* predominates.

ESSEXITE, where *acid labradorite* predominates.

GABBRO, where *basic labradorite* predominates.

KENTALLENITE, where *orthoclase* and *plagioclase* are present in equal proportions.

FELSPATHOIDAL GABBROS, where *felspathoids* replace feldspars, such as BOROLANITE, containing leucite pseudomorphs.

THERALITE and COVITE, containing nepheline.

THE GABBRO FAMILY comprises *gabbro* (augite and plagioclase), *olivine gabbro*, *norite* (hypersthene gabbro), *olivine norite*, *hyperite* (quartz norite), and *troctolite* (olivine and labradorite).

#### 4. The Ultrabasic Rocks.

**Minerals.**—Olivine, pyroxene, amphibole, biotite, iron ores, spinels, and occasionally garnets. A little feldspar is essential to picrites.

**Types.**—PICRITES, containing *olivine* and a *pyroxene* or *amphibole*, together with a *little feldspar*.

ALLIVALITE, containing *olivine* and *anorthite* only.

AMPHIBOLITE, with dominant *hornblende*.

HORNBLENDITE, *hornblende* dominant; *feldspar* absent.

PYROXENITE, with dominant *augite*; *feldspar* absent.

**HYPERSTHENITE**, with dominant *hypersthene*; *felspar* absent.

**ECLOGITE**, consisting of *emerald-green hornblende*, *grass-green augite*, and *red garnet*.

**PERIDOTITE**, with dominant *olivine*; *felspar* absent; comprising *dunite* (olivine rock), *harzburgite* (enstatite peridotite), *wehrlite* (diplage peridotite), *herzolite* (diplage enstatite peridotite), and others.

**SERPENTINE ROCK**, consisting chiefly of serpentine, often with *diplage* or *bastite*, and *spinels*.

## B. Hypabyssal Rocks.

**Structure.**—Porphyritic, granophyric, microgranitic, felsitic, ophitic, or granulitic; rarely glassy, usually holocrystalline.

### 1. The Quartz-Porphyry Family.

**Minerals.**—Those of the granite family.

**Types.**—**GRANITE PORPHYRY**, with both *quartz* and *felspar* phenocrysts.

**QUARTZ PORPHYRY**, with phenocrysts of *quartz* only.

**MICROGRANITE**, with no phenocrysts; groundmass *microgranitic*.

FELSITE, with no phenocrysts ; groundmass  
*felsitic*.

GRANOPHYRE, with *micropegmatitic* groundmass.

PITCHSTONE, with *glassy* groundmass full of microlites.

## 2 (a). The Porphyry Family.

**Minerals.**—Those of syenites and monzonites.

**Types.**—FELSPAR PORPHYRY (*orthophyre*), with *orthoclase* phenocrysts.

NEPHELINE PORPHYRY, with *nepheline* phenocrysts.

## 2 (b). The Porphyrite Family.

**Minerals.**—Those of the diorites.

**Types.**—PORPHYRITE, with *porphyritic felspars* in microcrystalline groundmass.

MARKFIELDITE, with *granophyric* groundmass.

## 3. The Dolerite Family.

**Minerals.** — Those of basic rocks and analcime.

**Types.**—DOLERITE, containing *plagioclase* and *augite*.

OLIVINE DOLERITE, containing *olivine* in addition.

TESCHENITES, or *analcime dolerite*.

MUGEARITE, with *olivine* and *augite* in a *trachytic* groundmass of *oligoclase* laths.

#### 4. Highly Differentiated Rocks.

Each of these is produced by the splitting up or differentiation of any one of the other rocks (in the form of magma) into two complementary ones—one light coloured and containing a predominance of felspathic constituents (*a leucocrate*), and the other dark coloured and containing a predominance of ferromagnesian constituents (*a melanocrate*).

##### Types.—

##### (a) LEUCOCRATES :—

APLITES, with *granular* structure.

PEGMATITES, with coarse *pegmatitic* structure.

BOSTONITES, with *trachytic* groundmass of felspar laths.

##### (b) MELANOCRATES :—

LAMPROPHYRES, with *biotite* or *hornblende* in a felspathic groundmass.

MONCHIQUITES, felspar absent; *biotite*, *olivine*, and *hornblende* present.

ALNOITE, felspar absent; *biotite*, *melilite*, and *perovskite* present.

### C. Volcanic Rocks.

**Structure.**—Perlitic, spherulitic, fluxional, trachytic, andesitic, granulitic, ophitic, felsitic, or glassy. Glass seldom quite absent.

#### 1. The Acid Rocks.

**Minerals.**—Orthoclase, oligoclase, albite, quartz, biotite, hornblende, augite, and cossyrite.

**Types.**—RHYOLITE, where *orthoclase* predominates.

SODA RHYOLITE (with *quartz pantellerite*), where *soda felspar* predominates.

DACITE, where *plagioclase* predominates.

TOSCANITE, where *plagioclase* and *orthoclase* are present in equal amounts.

#### 2. The Intermediate Rocks.

**Minerals.**—Orthoclase, andesine, labradorite, nepheline, leucite, nosean, biotite, hornblende, augite, and cossyrite.

**Types.**—TRACHYTE, where *orthoclase* predominates.

PHONOLITE, where *nepheline* replaces felspar.

LEUCITOPHYRE, containing large *leucite* crystals.

PANTELLERITE, with *soda felspars* and *cosssyrite*.

ANDESITE, where *plagioclase* predominates.

TRACHYANDESITE, where *plagioclase* and *orthoclase* are present in equal proportions.

### 3. The Basic Rocks.

**Minerals.**—*Plagioclase* (generally *labradorite*), *nepheline*, *leucite*, *hauyne*, *augite*, *olivine*, and iron ores.

**Types.**—BASALT, containing *augite* and *plagioclase*.

OLIVINE BASALT, containing *olivine* as well.

TEPHRITE, containing *augite*, *plagioclase*, and *nepheline* or *leucite*.

BASANITE, the same, with the addition of *olivine*.

NEPHELINE BASALT, containing *nepheline*, *augite*, and *olivine*.

LEUCITE BASALT, containing *leucite*, *augite*, and *olivine*.

MELILITE BASALT, containing *melilite*, *augite*, and *olivine*.

NEPHELINITE, containing *nepheline* and *augite* only.

LEUCITITE, containing *leucite* and *augite* only.

AUGITITE, containing *augite* and *magnetite* only in a glassy base.

LIMBURGITE, containing *augite*, *olivine*, and *magnetite* embedded in a glassy base.

KULAITTE, containing *hornblende*, *augite*, and *olivine* in a glassy base.

CIMINITE, containing *orthoclase* and *plagioclase* in equal proportions.

## APPENDIX I

### MORE ADVANCED METHODS OF IDENTIFYING MINERALS IN THIN SECTION

**Klein's Quartz Plate.**—A plate of quartz cut at right angles to the optic axis. Owing to circular polarisation, this plate is not dark between crossed nicols, but shows an interference tint. It forms the basis of an accurate method of determining extinction angles. It is inserted into a slot in the body tube of the microscope between crossed nicols, and the analyser, which should preferably be of the eyepiece form, rotated until the purplish violet interference tint (No. 18 of Newton's scale) appears. The slide is then placed on the stage, and the mineral whose extinction is to be measured found. The mineral is turned until it ceases to raise or lower the violet interference tint, No. 18. The angle between the cross-thread and the length, cleavage, or one set of twin lamellæ of the mineral, is the extinction angle.

**Quartz Wedge.**—A long wedge of quartz cut parallel to the vertical axis, which in quartz is the axis of least optical elasticity. It shows between crossed nicols the colours of Newton's scale, commencing at the thin end. It is used in determining the relative values of the axis of optical elasticity

and in finding the relative birefringence of minerals. Supposing such a wedge of quartz to be placed between crossed nicols over a section of a mineral polarising in a certain tint: if the axis of minimum elasticity of the wedge and mineral are parallel, the polarisation colour will rise according to Newton's scale; but if they are at right angles it will fall, because they will each tend to throw the polarised light out of phase in opposite directions. The wedge is inserted at  $45^\circ$  to the diagonals of the nicols and the direction of extinction of the mineral placed parallel to it. If the colour rises, the axis of least elasticity of the section is evidently parallel to the wedge; but if it falls, then the direction of greatest elasticity is parallel to the wedge. To confirm the observation in the latter case, the wedge may be pushed in until the colour falls to 0 of the scale—that is, it becomes grey or black. If in so doing the original colour of the section recurred  $n$  times, then the colour was of the  $(n + 1)$ th order.

**Selenite Plate.**—A thin plate of selenite is often supplied with polariscopes, for the purpose of detecting very slight double refraction. Its usefulness depends on the fact that it is easier to detect a change from one tint to another than from the very dark grey of feeble double refraction to black. A slight addition to the double refraction of a selenite polarising in a bright tint makes a marked change in the interference colour, and a double refraction that might otherwise escape observation is easily detected in this manner. The usual selenites employed give between crossed nicols the red of the

first order or blue green or orange of the second, and are mounted either on ordinary 3 in. by 1 in. glass slips or on a substage fitting. It is immaterial whether they be placed above or below the rock section. If the position and relative values of the axis of optical elasticity of the selenite be known, it can be used as a substitute for a quartz wedge, by observing whether the colour is raised or lowered by the mineral examined. The sensitive tint of a Klein's quartz plate is also useful for detecting small double refractions, but cannot be used as a substitute for a quartz wedge.

**Optical Sign.**—A uniaxial crystal whose axis of least elasticity is parallel to its vertical axis is called positive; and conversely, one whose axis of greatest elasticity is parallel to its vertical axis is called negative. In biaxial crystals, the axis of optical elasticity, which bisects the acute angle between the optic axis (the acute bisectrix), corresponds to the single optic axis of uniaxial crystals; and if it is the axis of least optical elasticity, the crystal is said to be positive; if of greatest elasticity, the crystal is negative.

**Etching and Staining.**—This is sometimes useful in determining rock-forming minerals where, owing to minuteness or other cause, the optical characters are insufficient. The principle involved is as follows:—Many silicates are attacked by HCl with the solution of the bases leaving a gelatinous mass of silica (*gel*) which can be stained, whilst the unchanged mineral usually cannot. In the case of the feldspars, HF is used, which volatilises the silica as  $\text{SiF}_4$ , leaving

a *gel* of alumina, which can also be stained. In either case the test is performed on a slide, from which the cover-glass has been removed by gentle heating and superfluous balsam wiped away with a little alcohol. On to the cleaned surface of the mineral to be investigated is placed one drop of the acid, by means of a rod,<sup>1</sup> and allowed to act for some time, according to circumstances. It is then washed off thoroughly, and a small pool of the stain (fuchsin or anilin blue) poured on. After allowing to stand a minute the dye is washed off, and, should the mineral not have taken a deep enough stain, the etching and staining process repeated.

After etching with HCl, olivine, serpentine, chlorite, feldspathoids, analcime, and anorthite *stain*.

After etching with HF, orthoclase *stains slightly*, plagioclase *stains deeply*, whilst quartz etches but does *not stain at all*.

**Borický's Microchemical Test.**—A drop of fluosilicic acid is placed on the section of the mineral to be examined (the other parts of the section may be protected by covering with Canada balsam) and allowed to evaporate slowly in a desiccator. As this takes place very slowly, gentle heating is advantageous. When the evaporating of the acid is completed, the section is examined under the microscope, and the fluosilicates of the various elements present in the mineral will have crystallised out. If they are too minute for identification, they may be recrystallised by adding a drop of water and

<sup>1</sup> The rod should be of platinum or of glass coated with Canada balsam.

allowing it to evaporate slowly in the air. The various alkaline and alkaline-earth elements give rise to characteristic crystals as follows:—

POTASSIUM.—Minute isotropic cubes and octahedrons.

SODIUM.—Hexagonal prisms with weak D.R., negative; prisms longer the more calcium there is in solution.

CALCIUM.—Thornlike, ramifying groups and crystals, rarely straight edged, with moderate D.R.; upon adding sulphuric acid bunches of long, needle-like prisms of gypsum are formed with weak double refraction.

MAGNESIUM.—Rhombohedral crystals with sharp edges and plane faces, polarising in bright second-order colours. To confirm magnesium, redissolve them and add ammonium chloride and ammonia, then place a crystal of sodium phosphate at the edge of the drop. After a time, coffin-shaped crystals of struvite, usually hemimorphic—*i.e.* ends differently terminated—are formed.

IRON.—Crystals exactly like those of magnesium fluosilicate, from which they might be distinguished by giving a blue stain with potassium ferricyanide.

ALUMINIUM.—Fluosilicate gelatinous.

PHOSPHORUS.—To detect this in phosphates such as apatite, use  $\text{HNO}_3$  instead of  $\text{HF}$ , and add ammonium chloride, ammonia, and magnesium sulphate. Formation of struvite indicates phosphate.

## APPENDIX II

### TABLE FOR THE IDENTIFICATION OF ROCK-FORMING MINERALS IN THIN SECTION

The mineral should be examined—

- (1) As to whether it is colourless, coloured, or opaque ;
- (2) As to its I.R. relative to that of Canada balsam, by Becké's method ;
- (3) As to its behaviour towards polarised light ;
- (4) As to its characteristic structures, such as cleavages, inclusions.

#### A. MINERALS USUALLY COLOURLESS AND TRANSPARENT

##### 1. Index of Refraction (I.R.) very low (lower than that of Canada balsam ( $= 1.54$ )).

(a) *Isotropic. I.R. very low:—*

SODALITE.—Usually allotriomorphic, with many anisotropic inclusions not regularly arranged ; occasionally faintly coloured green, blue, or yellow ; attacked by HCl ; *found in intermediate rocks.*

ANALCIME.—Usually allotriomorphic, except when occurring in cavities, then forms

polygonal sections, often with weak anomalous double refraction; attacked by HCl; *found in basic hypabyssal and volcanic rocks.*

**NOSEAN.**—Polygonal crystals with a zonal arrangement of inclusions forming either a dark border or a dark centre to the crystal; may be coloured faintly blue or yellow; attacked by HCl; *found in intermediate rocks.*

**FLUORITE.**—Usually allotriomorphic, unless occurring in cavities; if coloured at all, is pale violet; not soluble in HCl; *found in acid rocks, especially in granites.*

**LEUCITE.**—Polygonal crystals, often with a radial or peripheral arrangement of inclusions. Small crystals isotropic, larger ones show intersecting systems of twin lamellæ and very weak double refraction; *found in intermediate and basic volcanic rocks.*

(b) *Anisotropic. I.R. very low:—*

**TRIDYMITE.**—D.R. moderate; positive; in tile-like aggregates; soluble in boiling NaOH; *found in rhyolites and trachytes.*

(c) *Anisotropic. I.R. low; D.R. moderate:—*

**ORTHOCLASE.**—D.R. less than that of quartz; Carlsbad twins common, usually somewhat cloudy from decomposition; *commonest in acid and intermediate rocks.*

**MICROCLINE.**—Fine twin lamellæ crossing at right angles; lamellæ spindle-shaped; *found in granites.*

**ALBITE.**—Albite and rarely pericline twin lamellæ; maximum extinction angle  $16^{\circ}$ ;

lamellæ parallel-sided; *found in acid and intermediate rocks.*

PERTHITE.—Orthoclase containing thin plates of albite or oligoclase intercalated parallel to the orthopinakoid. When fine-grained it is called *micropertlite*; *found in acid and intermediate rocks.*

2. I.R. low (equal to or greater than that of Canada balsam (1.54 to 1.6)).

(a) *Moderate D.R.*:—

QUARTZ.—Hexagonal sections and grains, always clear, inclusions frequent; *usually found in acid rocks.*

OLIGOCLASE.—Albite twinning common, pericline twinning more rare; often cloudy; maximum extinction angle  $6^{\circ}$ ; cleavages crossing nearly at right angles, difficult to see; *found in acid rocks.*

ANDESINE.—Like oligoclase, but maximum extinction angle  $22^{\circ}$ ; *found in intermediate rocks.*

LABRADORITE.—Like oligoclase, but maximum extinction angle  $27^{\circ}$  to  $45^{\circ}$  from the direction of least optical elasticity to the vertical cross-thread; *found in basic and intermediate rocks.*

ANORTHITE.—Like oligoclase, but maximum extinction angle  $50^{\circ}$  from the direction of least optical elasticity to the vertical cross-thread (use quartz wedge); *found in ultrabasic rocks.*

NEPHELINE.—D.R. lower than that of orthoclase; often turbid from decomposition; hexa-

gonal and rectangular sections—the former isotropic, the latter giving straight extinction; *found in intermediate and basic volcanic rocks.*

ELÆOLITE.—Massive variety of nepheline; allotriomorphic; rough cleavage cracks; straight extinction; *found in syenites.*

SERPENTINE.—Aggregate of minute scales with a mesh or lattice structure often nearly isotropic; *found in basic and ultrabasic rocks.*

(b) *Very strong D.R. :—*

MUSCOVITE.—Strong cleavage parallel to base; extinction straight or nearly so; forms usually lath shaped; may be bent and with frayed-out ends; basal sections polarise in dull grey tint, *found in granites as a primary mineral*; a frequent decomposition product from orthoclase.

CALCITE.—Three cleavages parallel to the faces of the rhombohedron; I.R. varies from low to high according to plane of polarisation of light; lamellar twinning characteristic; its very high D.R. gives a peculiar pearly effect between crossed nicols.

3. I.R. high (1·6 to 1·72).

(a) *D.R. weak :—*

APATITE.—Straight extinction; short prisms or needles with transverse partings or rarely isotropic hexagonal sections; negative.

MELILITE.—Straight extinction; peg-structure; lath shaped or allotriomorphic; *found in basic volcanic rocks.*

ZOISITE.—Colourless prisms and granules with straight extinction; *found in altered rocks.*

(b) *D.R. moderate* :—

ENSTATITE.—Straight extinction; square sections with truncated corners and columns; if coloured at all, very pleochroic; alters to bastite; two cleavages at  $87^{\circ}$ .

TOPAZ.—Straight extinction; prisms and grains occasionally coloured wine yellow; *found in acid rocks.*

(c) *D.R. strong* :—

OLIVINE.—Straight extinction; six-sided sections or more usually granular; traversed by marked irregular cracks along which serpentinisation commences; no visible cleavage; sometimes alters at the edges to limonite; *found in basic rocks.*

TREMOLITE.—Maximum extinction angle  $15^{\circ}$ ; long, needle-shaped crystals; *found in metamorphosed limestones.*

DIOPSIDE.—Maximum extinction angle  $38^{\circ}$ ; two cleavages at  $87^{\circ}$ ; *found in some ultrabasic rocks.*

#### 4. I.R. very high (above 1.7).

(a) *Isotropic* :—

SPINEL.—Colourless to pale pink octahedrons and grains; I.R. considerably less than that of garnet; *found in certain peridotites.*

COMMON GARNET.—Sometimes coloured pale brownish red; polygonal sections and grains.

(b) *D.R. strong* :—

ZIRCON.—Obtusely terminated prisms; positive;

may be coloured yellowish or brownish; *found in microscopic crystals in granites, in larger crystals in syenites.*

**TINSTONE.**—Grains and prisms; positive; may be coloured yellowish or brownish; *found in altered granites associated with tourmaline and topaz.*

## B. MINERALS USUALLY COLOURED BUT TRANSPARENT IN THIN SECTION

1. **I.R. very low** (lower than that of Canada balsam (less than 1.54)).

**HAÜYNE.**—Pale blue to colourless; isotropic; marginal or zonal arrangement of inclusions; distinguish from nosean by giving an abundance of needles of gypsum when decomposed by HCl; *found in basic volcanic rocks.*

2. **I.R. low** (equal to or greater than that of Canada balsam (1.54 to 1.6)).

(a) *D.R. weak* :—

**CHLORITE.**—Light green to yellowish pleochroic plates, leaves, and scales; perfect basal cleavage; essentially a secondary mineral; *resulting from the decay of biotite, hornblende, or augite.*

(b) *D.R. moderate* :—

**SERPENTINE.**—Light green aggregate of scales and fibres, which by overlapping may make the section nearly isotropic; occasionally weakly pleochroic; *resulting from the decay of olivine, or rarely of hornblende or augite.*

(c) *D.R. very strong* :—

BIOTITE.—Yellow to brown or rarely green pleochroic lath-shaped sections (darkest when placed parallel to short axis of nicol); deep brown, hexagonal, nearly isotropic basal sections; perfect cleavage parallel to base; lamellar twinning parallel to base occasionally observed; extinction straight or up to  $3^{\circ}$ . Pleochroic halos round inclusions; axis of least elasticity parallel to cleavage.

3. I.R. high (1.6 to 1.72); *D.R. strong*.

(a) *Non-pleochroic* :—

AUGITE.—Pale brown or green, or almost colourless; purplish-brown varieties rich in titanium, and green variety rich in soda are slightly pleochroic; two cleavages at  $87^{\circ}$ ; eight-sided and rhomboidal sections; latter extinguish at  $45^{\circ}$  or more from cleavage; lamellar twinning not infrequent.

(b) *Somewhat pleochroic* :—

ÆGIRINE.—Emerald green; maximum extinction angle  $5^{\circ}$ ; in laths and sub-rectangular crystals; two cleavages at  $87^{\circ}$ ; axis of greatest elasticity nearly parallel to cleavage and length of laths.

(c) *Very pleochroic* :—

HYPERSTHENE.—Salmon pink and reddish yellow to sea green; in eight-sided sections and columns; straight extinction; axis of least elasticity parallel to length; two cleavages at  $87^{\circ}$ ; alters to bastite; often schillerised.

**TOURMALINE.**—Brown, green, blue, or pink, with very strong pleochroism; positive; in needles, prisms, and grains; deepest colour occurs when length of section is perpendicular to short axis of nicol. Basal sections three to nine sided, isotropic; *found in acid rocks.*

**RIEBECKITE.**—Greenish brown to indigo blue pleochroism; extinction angles less than  $6^{\circ}$ ; two cleavages at  $124^{\circ}$ ; axis of greatest elasticity nearly parallel to cleavages in longitudinal sections; usually allotriomorphic; *found in microgranites and trachytes.*

**GLAUCOPHANE.**—Blue to reddish violet and colourless in prisms, with maximum extinction angle  $3^{\circ}$  to  $11^{\circ}$  from axis of least elasticity to vertical axis; *found in metamorphosed diorites.*

**COSSYRITE.**—Brownish red to coffee brown and black in laths and six-sided sections; *found in pantellerites.*

**HORNBLENDE.**—Green to yellow or brown to yellow laths and six-sided sections; extinction angle  $10^{\circ}$  to  $20^{\circ}$  from axis of least elasticity; two cleavages at  $124^{\circ}$ .

**ACTINOLITE.**—Green; in needles; maximum extinction angle  $18^{\circ}$ ; often a secondary mineral, formed from pyroxene, then called *uralite.*

#### 4. I.R. very high (above 1.7).

(a) *Isotropic* :—

**MELANITE GARNET.**—Brown; in grains; zonal

structure; numerous cracks; *found in feldspathoidal gabbros.*

**PYROPE GARNET.**—Blood red; in grains; often with fibrous shell called *Kelyphite*; *found in plutonic and other rocks in areas of dynamo-metamorphism.*

**PLEONASTE.**—Green, in six-sided and polygonal sections and in grains; *found in peridotites.*

**PICOTITE.**—Deep brown; in grains; often with crystallographic boundaries, and in polygonal sections; *found in peridotites.*

**CHROMITE.**—Very deep brown or black; *found in peridotites.*

**PEROVSKITE.**—Violet brown to grey or yellow; in cubes and octahedrons; large crystals with anomalous D.R.; *found in melilite basalts.*

(b) *D.R. strong* :—

**SPHENE.**—Irregular grains or wedge-shaped crystals; reddish-brown, feeble pleochroism; marked cleavage; polarisation colours obscured by strong colour of the mineral; *found in granites and syenites.*

**RUTILE.**—Yellow to red and reddish brown prisms and needles; also as fine hairs in quartz; knee-shaped and heart-shaped twins characteristic; frequently presents a peculiar interlaced structure called *sagenite*.

**MONAZITE.**—Thick tablets of light yellowish colour; infrequent in igneous rocks; two cleavages; I.R. higher than that of epidote; *found in a few syenites.*

**EPIDOTE.**—Pale yellow to colourless grains and

rods; two cleavages; straight extinction; pleochroic; axis of greatest elasticity nearly at right angles to length of rods.

WITHAMITE.—A pink to yellow pleochroic variety of epidote.

THULITE.—A pink to yellow pleochroic variety of zoisite; the epidotes and zoisites are usually secondary, resulting from the decay of lime-bearing minerals such as hornblende and plagioclase.

### C. OPAQUE MINERALS

MAGNETITE.—Black by reflected light; square sections and grains; metallic lustre.

ILMENITE.—Hexagonal sections and grains; alters along three systems of lamellæ intersecting at  $60^\circ$  to a white substance (leucoxene, a variety of sphene); metallic lustre.

PYRITES.—Square sections and grains; brass yellow by reflected light; metallic lustre.

GOLD.—Pale golden yellow grains *in certain diorites*; distinguished from pyrites by colour and hardness; metallic lustre.

NATIVE IRON.—Steely grey metallic lustre; much brighter than that of magnetite, with which it is associated; distinguished by pouring on a solution of  $\text{CuSO}_4$ , which turns it copper coloured; *found in certain basalts*.

GRAPHITE.—Light black to brownish black flakes of hexagonal or rounded outline; metallic

lustre; flakes usually very minute; *rare in igneous rocks.*

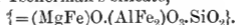
*N.B.*—The habitats given in these tables for the minerals are those in which they are most commonly found; where none are given, it is because the mineral occurs in a large variety of rocks.



## GLOSSARY-INDEX

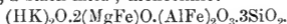
- Actinolite* (p. 51),  $\text{CaO} \cdot 3(\text{MgFe}) \cdot 4\text{SiO}_2$ ; a monoclinic amphibole.
- Adamellite* (p. 40), an acid plutonic rock in which plagioclase and orthoclase are present in equal proportions—*e.g.* Shap granite.
- Aegirine* (p. 44),  $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 4\text{SiO}_2$  plus a little augite; a monoclinic soda pyroxene.
- Allotriomorphic* (p. 105), possessing irregular boundaries, not those proper to the mineral; fitting into an interspace between the other constituents.
- Amphiboles* (p. 26), a group of minerals, of which hornblende is the most important; essentially metasilicates of iron, magnesium, and calcium; rhombic, monoclinic, and triclinic; have two cleavages at  $124^\circ$  from each other.
- Analcime* (p. 69),  $\text{NaAl}(\text{SiO}_3)_2 + \text{H}_2\text{O}$  cubic.
- Analyser* (p. 11), any instrument that will detect the polarisation of light. It acts by allowing light to pass through only when polarised in a certain plane.
- Andesites* (p. 80), the volcanic representatives of the diorites, containing essentially plagioclase and hornblende, or pyroxene, or biotite.
- Anisotropic* (p. 18), crystals whose elasticity towards light varies with the direction are said to be anisotropic, or doubly refracting. Light vibrating in different planes is transmitted by anisotropic crystals with different velocities and anisotropic sections are light between crossed nicols, except in certain positions.
- Anorthoclase* (p. 44), a potash-soda felspar, probably a perthite in which the perthitic structure is too fine to be resolved by the microscope.
- Apatite* (pp. 35 and 38),  $3\text{Ca}_3(\text{PO}_4)_2 + \text{CaF}_2$  or  $\text{CaCl}_2$ ; hexagonal.

*Augite* (pp. 48, 53, and 61), a monoclinic pyroxene composed of  $m$  molecules of diopside,  $\{=\text{CaO} \cdot (\text{MgFe})\text{O} \cdot 2\text{SiO}_2\}$ , and  $n$  molecules of Tschermak's silicate,



*Basalts* (pp. 82-88), the volcanic representatives of the gabbros containing augite, plagioclase, and frequently olivine.

*Biotite* (p. 31), a black mica; monoclinic:



*Bronzite* (p. 63), a rhombic pyroxene intermediate between enstatite and hypersthene.

*Calcite* (pp. 71 and 89),  $\text{CaCO}_3$ ; hexagonal (rhombohedral).

*Canada balsam* (p. 1), a resinous substance a solution of which in xylol is used for mounting microscopical preparations; isotropic I.R. = 1.54, the same as that of quartz.

*Chlorite* (p. 37), hydrated silicate of magnesia, iron, and alumina; monoclinic.

*Cossyrite* (p. 75), a triclinic mineral having the habit of an amphibole:  $2\text{Na}_2\text{O} \cdot 10\text{FeO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3 \cdot 15\text{SiO}_2$ .

*Crossed nicols* (p. 9), two nicols prisms with their short diagonals at right angles to each other, so that the light polarised by the one is rejected by the other and the field is dark.

*Cross-threads or cross-wires* (p. 9), two thin spider threads crossing at right angles in the focus of the eyepiece of a petrological microscope. Their intersection lies in the optic axis of the instrument. The eyepiece is provided with a catch which locks it in such a position that the cross-threads are parallel to the axes of the nicols.

*Cryptocrystalline* (p. 76), formed of crystals too small to be resolved by the microscope.

*Crystallites* (p. 73), embryo crystals possessing neither a true crystalline form nor the power of reacting with polarised light; they represent *the first* products of crystallisation of a very viscous liquid, such as a cooling lava.

*Dacite* (p. 79), a volcanic rock corresponding to granodiorite, containing quartz, plagioclase, the plutonic rock, and biotite in a glassy groundmass.

- Devitrification* (p. 76), the alteration of glass by spontaneous crystallisation, which may take place very slowly at ordinary temperatures, but is much accelerated by heat and moisture.
- Diallage* (p. 49), a variety of augite laminated parallel to the orthopinakoid by the intercalation along parallel planes of minute plates and rods.
- Diopside* (p. 54),  $\text{CaO}(\text{MgFe})\text{O} \cdot 2\text{SiO}_2$ ; a monoclinic pyroxene.
- Diorite* (p. 46), a plutonic rock composed essentially of plagioclase feldspar and hornblende.
- Ditroite* (p. 45), a feldspathoidal syenite characterised by a variety of intergrown feldspars, sodalite, and a small quantity of biotite.
- Dolerite* (p. 66), a hypabyssal rock, corresponding to the plutonic gabbro, containing labradorite, augite, and frequently olivine.
- Double refraction* (pp. 19 and 20), the power possessed by most crystals of refracting light unequally according to the planes in which it is vibrating. A *doubly refracting*, or *anisotropic*, crystal has three indices of refraction, corresponding to the three axes of optical elasticity, the least elasticity always corresponding to the greatest refractive index. In uniaxial crystals two of the refractive indices are equal.
- Elæolite* (p. 45), a name given to nepheline when occurring massive. It is of a brownish colour and has a greasy lustre.
- Enstatite* (p. 54),  $\text{MgSiO}_3$  with a trace of  $\text{FeSiO}_3$ ; a rhombic pyroxene.
- Epidiorite* (p. 67), a dolerite in which the augite has been changed into hornblende from dynamic or thermal causes.
- Extinction* (p. 16), darkness between crossed nicols of an anisotropic mineral which takes place in certain positions only.
- Extinction angle* (p. 17), the angle between some fixed direction, such as the cleavage, in an extinguished crystal section, and the short diagonal of one of the nicols.
- Eyepiece* (p. 4), a combination of lenses which magnifies the real image of the object formed by the objective.
- Felsite* (p. 60), an acid hypabyssal rock having a groundmass com-

posed of cryptocrystalline matter, giving a dappled effect between crossed nicols.

*Felspars* (p. 26), a group of silicates having the general formula  $(\text{Na}_2\text{K}_2\text{Ca})\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$ . When monoclinic they are called orthoclase; when triclinic they are called plagioclase.

*Felspathic*, of the nature of felspar.

*Foyaite* (p. 45), a syenite in which half the orthoclase is replaced by nepheline.

*Gabbro* (p. 48), a basic plutonic rock containing plagioclase, diallage, and frequently olivine.

*Glomeroporphyritic* (p. 77), the packing together of porphyritic crystals, so that whilst idiomorphic towards the groundmass they are allotriomorphic towards each other.

*Granite* (p. 29), a plutonic rock containing essentially quartz, orthoclase, and a mica.

*Granodiorite* (p. 40), an acid plutonic rock in which orthoclase largely predominates over plagioclase.

*Granophyre* (p. 61), a hypabyssal rock having a groundmass of micropegmatite, usually acid but not necessarily so.

*Granulitic basalt* (p. 84), a basalt whose groundmass is composed of plagioclase laths, in the interspaces between which are augite granules and glass.

*Häüyne* (p. 86),  $3(\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2)+2\text{CaSO}_4$ ; a cubic feldspathoid.

*Holocrystalline* (p. 91), built up entirely of crystals.

*Hornblende* (pp. 42 and 81), metasilicate of iron, alumina, lime, and magnesia; a monoclinic amphibole.

*Hyalopilitic* (p. 81), a term applied to a groundmass composed of plagioclase, microlites, and glass, with or without fluxional arrangement.

*Hypabyssal* (p. 25), a term applied to rocks which have consolidated at comparatively shallow depths in the earth's crust as small intrusions. Such rocks are usually medium grained and intermediate in structure between volcanic and plutonic rocks.

*Hyperite or Quartz norite* (p. 51), a basic plutonic rock containing essentially hypersthene, plagioclase, and quartz.

*Hypersthene* (p. 51),  $(\text{MgFe})\text{SiO}_3$ ; a rhombic pyroxene.

*Idiomorphic* (p. 33), having its crystalline form properly developed (of crystals).

*Ilmenite* (p. 64),  $\text{FeTiO}_3$ ; a hexagonal iron ore.

*Index of refraction, I.R.; refractive index* (p. 19),  $= \frac{\sin i}{\sin r}$  where  $i$  = angle of incidence and  $r$  = angle of refraction of a ray of light passing from one medium to another; it is a measure of the relative velocities of light in different media.

*Interference colours* (p. 13), the colours seen in an anisotropic section viewed between crossed nicols, due to the interference of some colour components of white light leaving a coloured residue.

*Isotropic* (p. 19), the power of remaining dark for every position of the section between crossed nicols possessed by glass and cubic crystals. Such bodies are optically similar in all directions.

*Kaolin* (p. 33),  $2\text{H}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ; monoclinic.

*Lamprophyre* (p. 69), a highly differentiated hypabyssal rock characterised by abundant idiomorphic biotite and hornblende embedded in a felspathic base.

*Laurvigite* (Larvigite) (p. 44), a soda syenite consisting essentially of anorthoclase, brown hornblende, aegirine, biotite, and magnetite.

*Leucite* (pp. 79 and 86),  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$ ; a cubic felspathoid.

*Leucitophyre* (p. 79), a volcanic rock composed of phenocrysts of leucite, nosean, and aegirine augite in a groundmass of microlites of these minerals and of sanidine.

*Lherzolite* (p. 54), a peridotite containing olivine, diopside, enstatite, and picotite.

*Limburgite* (p. 88), a basic volcanic rock containing neither feldspars nor felspathoids, but only olivine, augite, and magnetite in a glassy base.

*Limonite* (p. 88), hydrated  $\text{Fe}_2\text{O}_3$ , usually amorphous.

*Magma* (p. 96), the fused mass of silicates in the earth's crust which by consolidation gives rise to an igneous rock.

*Magnetite* (p. 38),  $\text{Fe}_3\text{O}_4$ , an iron ore; cubic.

- Markfieldite* (p. 63), a granophyre corresponding to a diorite in composition.
- Melilite* (p. 87),  $12(\text{CaMg})\text{O} \cdot 9(\text{AlFe})_2\text{O}_3 \cdot 9\text{SiO}_2$ ; a tetragonal feldspathoid.
- Microcline* (p. 34), a potash felspar  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ ; triclinic.
- Microgranite* (p. 56), an acid hypabyssal rock having a structure like that of a granite, but on a much smaller scale, and like a granite consisting largely of quartz and felspar.
- Microgranitic* (p. 56), a term applied to a groundmass composed of interlocking quartz and felspar crystals, like that of a microgranite.
- Microclites* (p. 73), embryo crystals, which though not possessing the fully developed crystal form of the mineral, nevertheless behave as perfect crystals towards polarised light.
- Micropegmatite* (pp. 34, 60, and 61), an intimate intergrowth of quartz and felspar in which these two minerals have crystallised simultaneously; sometimes called graphic from a fancied resemblance to Hebrew writing.
- Microperthite* (p. 39), an intergrowth of orthoclase and plagioclase in which the latter occurs in thin plates intercalated parallel to a crystal face.
- Minette* (p. 69), a lamprophyre consisting essentially of orthoclase and biotite.
- Monazite* (p. 113), phosphate of cerium and lanthanum; monoclinic; used for the manufacture of incandescent gas mantles.
- Muscovite* (p. 31), a white mica,  $\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ ; monoclinic.
- Nepheline* (pp. 45 and 77),  $(\text{NaK})_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ; a hexagonal feldspathoid.
- Nevadite* (p. 73), a rhyolite in which the quartz and felspar phenocrysts are so numerous and large as to give the rock a granite appearance.
- Newton's Scale of Colours* (p. 14), the order in which the interference colours occur in an anisotropic section as the thickness is gradually increased from zero upwards.
- Nicol's Prism* (pp. 4 and 10), a rhombohedron of calcite which after slitting diagonally and recementing with Canada balsam has had the ends ground to a particular angle. A beam of common light entering at one end emerges polarised, because

all light except that polarised parallel to the short diagonal has been reflected away at the junction between the two halves.

*Nosean* (p. 78),  $3(\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2)2\text{Na}_2\text{SO}_4$ ; a cubic feldspathoid.

*Objective* (p. 4), a combination of lenses which forms in the tube of the microscope a real image of any object on the stage.

*Obsidian* (p. 73), a rhyolite consisting almost entirely of glass which usually contains crystallites.

*Olivine* (p. 50),  $(\text{FeMg})_2\text{SiO}_4$ ; rhombic.

*Ophitic structure* (p. 67), the crystallisation of one mineral, such as augite, in plates enclosing lath-shaped feldspars.

*Optic axis* (p. 18), a direction in a crystal in which there is no double refraction.

*Optical elasticity, axes of* (p. 16), three directions in a crystal parallel to which light entering the crystal becomes polarised. They correspond in direction to the refractive indices of a doubly refracting crystal, and are said to be least when the I.R. is greatest, and *vice versa*.

*Orthoclase* (p. 33), potash feldspar,  $\text{K}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$ ; monoclinic.

*Pantellerites* (p. 74), a group of volcanic rocks found in the Isle of Pantellaria of acid and subacid composition. They are rich in soda and often contain cossyrite.

*Peridotite* (p. 54), a basic plutonic rock composed chiefly of olivine without feldspar.

*Perlitic structure* (p. 76), a series of spiral cracks traversing glassy rocks, due to their contraction on cooling.

*Perovskite* (p. 88),  $\text{CaTiO}_3$ ; cubic.

*Petrological microscope* (p. 4), the microscope used for examining rocks. It consists of a brass stand into which are fitted (a) polariser and condenser for controlling the light; and (b) objectives and eyepiece.

*Phenocryst* (p. 37), a large crystal of a rock constituent which also forms a second generation of smaller crystals in the groundmass.

*Phonolite* (p. 77), the volcanic representative of nepheline syenite, containing nepheline, sanidine, generally nosean, and aegirine.

- Picotite* (p. 54), a spinel  $(\text{FeMg})\text{O} \cdot (\text{CrFeAl})\text{O}_3$ ; cubic.
- Picrites* (p. 53), coarse-grained rocks containing olivine, augite, or hornblende, and a little felspar; usually considered plutonic.
- Pilotaxitic* (p. 81), composed of felspar laths felted together, without glass, but often with fluxional arrangement.
- Pitchstone* (p. 73), sometimes a volcanic but often a hypabyssal rock consisting of glass crowded with crystallites and microlites giving the rock a *pitchy* lustre.
- Plagioclase* (p. 31), a triclinic felspar of the formula:  
 $(\text{Na}_2\text{Ca})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ .
- Pleochroic halos* (p. 30), dark spots in biotite surrounding small inclusions of apatite and zircon; said to be due to the radioactivity of the enclosed mineral.
- Pleochroism* (p. 21), the power which some crystals have of appearing differently coloured according to the plane of polarisation of the light which is passed through them.
- Pleonaste* (p. 55),  $(\text{MgFe})\text{O}(\text{AlFe})_2\text{O}_3$ ; a spinel; cubic.
- Plutonic rocks* (p. 24), coarse-grained igneous rocks which have consolidated at considerable depths in the earth's crust.
- Poecilitic structure* (p. 54), the arrangement of small olivine grains in a large plate of augite; or hornblende, giving rise to *lustre-mottling* in hand specimens.
- Polarisation colours* (p. 11). See Interference colours.
- Polarised light* (p. 10), light which vibrates in one plane only.
- Polariser* (p. 4), any instrument for polarising light—that is, for suppressing all components which are not vibrating in a particular plane.
- Porphyritic* (p. 37), having porphyritic crystals or phenocrysts, *q.v.*
- Pyrites* (p. 38),  $\text{FeS}_2$ ; cubic.
- Pyroxenes* (p. 44), essentially metasilicates of magnesia and iron, sometimes with lime and alumina, rhombic and monoclinic; two (prismatic) cleavages meeting at  $87^\circ$ .
- Quartz* (p. 34),  $\text{SiO}_2$  (silica); hexagonal.
- Refraction* (p. 19), the bending of light resulting from its change of velocity in passing from one medium to another.

- Resorption* (p. 80), the decompositions of the margins of crystals by the caustic action of the still fluid groundmass.
- Rhyolites* (p. 72), the volcanic representatives of the granites, containing quartz and felspar crystals set in a glassy base, which may be clear or devitrified.
- Riebeckite* (p. 57),  $\text{Na}_2\text{O} \cdot \text{F}_2\text{O}_3 \cdot 4\text{SiO}_2$ , a soda amphibole; monoclinic.
- Rubislaw granite* (p. 29), a grey granite from Rubislaw, near Aberdeen, containing quartz, orthoclase, plagioclase, muscovite, biotite, and microcline.
- Rutile* (p. 34),  $\text{TiO}_2$ ; tetragonal.
- Sanidine* (p. 74), a clear variety of orthoclase found in trachytes and other volcanic rocks, characterised by well-defined transverse cracks.
- Schiller* (p. 53), a peculiar lustre shown by hypersthene and some other minerals, due to minute inclusions arranged in a parallel manner.
- Serpentine* (p. 50),  $2\text{M}_2\text{O} \cdot 3(\text{MgFe})\text{O} \cdot 2\text{SiO}_2$ ; a secondary mineral usually formed from olivine.
- Shap granite* (p. 36), the red porphyritic granite from Wasdale Crag, Shap, Westmoreland; noted for its porphyritic orthoclase, abundant plagioclase, and accessory sphene.
- Sodalite* (p. 45),  $3(\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2) + 2\text{NaCl}$ ; a cubic feldspathoid.
- Sphene* (p. 38),  $\text{CaO} \cdot \text{SiO}_2 \cdot \text{TiO}_2$ ; monoclinic.
- Spherulites* (pp. 63 and 75), little spheres built up of radiating bundles of felspar needles occurring in hypabyssal and volcanic rocks.
- Spinel* (p. 54),  $\text{MgO} \cdot \text{Al}_2\text{O}_3$ ; cubic; pleonaste, picotite, and chromite; are also called spinels because they result from the replacement of the  $\text{MgO}$  and  $\text{Al}_2\text{O}_3$  by other similar oxides without change in crystal form.
- Stage* (p. 4), the little platform of a microscope on which the slides are placed. It should rotate concentrically with the optic axis of the instrument.
- Syenite* (p. 41), an intermediate plutonic rock composed essentially of orthoclase and hornblende or augite or biotite.
- Tachylyte* (p. 82), a basic volcanic rock composed almost entirely of glass.

- Tephrite* (p. 86), a basalt in which part of the plagioclase is replaced by either nepheline or leucite.
- Teschenite* (p. 69), a dolerite containing analcime as an essential constituent.
- Tinstone* (p. 110),  $\text{SnO}_2$  ; tetragonal.
- Tourmaline* (p. 61), a complex borosilicate of various bases ; hexagonal.
- Trachytes* (p. 77), the volcanic representatives of the syenites, consisting chiefly of sanidine as phenocrysts and in the groundmass.
- Trachytic groundmass* (p. 77), a groundmass composed of sanidine microlites having a parallel disposition.
- Tremolite* (p. 109),  $\text{CaO} \cdot 3\text{MgO} \cdot 4\text{SiO}_2$  ; a monoclinic amphibole.
- Tridymite* (p. 106),  $\text{SiO}_2$ , silica ; possibly hexagonal.
- Troctolite* (p. 51), a basic plutonic rock consisting of labradorite and olivine.
- Tuff* (p. 88), the rock resulting from the consolidation of volcanic ash.
- Twin lamellæ* (p. 31), the thin plates of which certain twinned crystals are built up. Alternate plates are similar, and adjacent plates mirror images of each other.
- Uralite* (p. 68), a fibrous green hornblende resulting from the alteration of augite.
- Volcanic rocks* (p. 72), rocks which have been extruded—*i.e.* poured out as lavas—over the earth's surface.
- Zircon* (p. 35),  $\text{ZrSiO}_4$  ; tetragonal.
- Zoning* (p. 47), the arrangement of a crystal in concentric layers, or the disposition of its inclusions in lines parallel to its crystal faces.

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